Theory of Characteristic modes application to MIMO Antennas

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Abstract

Fourth Generation (4G) and fifth Generation (5G) wireless communication devices rely on multiple-input-multiple-output (MIMO) technology to provide enhanced data rates. Antenna design for MIMO systems is a challenging task in any communication system. Theory of characteristic modes (TCM) was proposed to provide some insight into the design and analysis of antennas.

This work will focus on the introduction of TCM and will discuss its application in various areas. It will also discuss the application of TCM to printed MIMO antenna design. A systematic method was developed with the help of TCM to predict, whether the isolation between the adjacent MIMO antenna elements with the help of defected ground structures (DGS) can be enhanced or not. On an average 11 dB of isolation enhancement was achieved for the MIMO antennas under consideration. The presence of the slots in the chassis was investigated with the help of TCM, and a 4-element MIMO Slot frequency reconfigurable antenna was presented. The physical mechanism behind frequency reconfigurability with the help of TCM was also investigated. This presentation will also highlight the shortcomings of the TCM approach such as the use of the chassis as a main radiating element and the antenna elements as an exciter for frequencies greater than 2 GHz.

Keywords: PIFA, Monopole, Slot Antenna, multiple-input-multiple-output (MIMO), Theory of characteristic modes (TCM), chassis

Biography

ASIM GHALIB received BSc and MSc in Electrical Engineering from the University of Engineering and Technology, Peshawar, Pakistan in 2011 and 2014, respectively. He obtained his PhD in Electrical Engineering in May 2018 from King Fahd University of Petroleum and Minerals (KFUPM), Dhahran, Saudi Arabia. He is currently working as a Visiting Research Scholar at University of Central Florida (UCF), Florida, USA.

His research interests include printed MIMO antennas, millimeter wave antennas, and design and analysis of MIMO antennas based on the theory of characteristic modes. He was the recipient of the best paper award at the IEEE Middle East Conference on Antenna and Propagation. His work resulted in several publications in international journals and conferences

Presentation Outline

Introduction

Background
Literature Review

Isolation enhancement by DGS using TCM
Frequency Reconfigurability and Slot analysis using TCM
Investigating the effect of real antennas on chassis using TCM

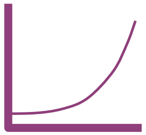
Conclusion

Introduction

Avalanche of
Traffic Volume

Further expansion of mobile broadband

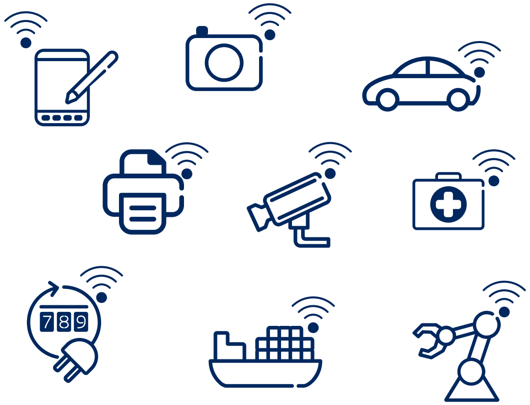
Additional traffic due to communicating machines



“1000x in ten years”

Massive growth in
Connected Devices

“Communicating machines”



“50 billion devices in 2020”

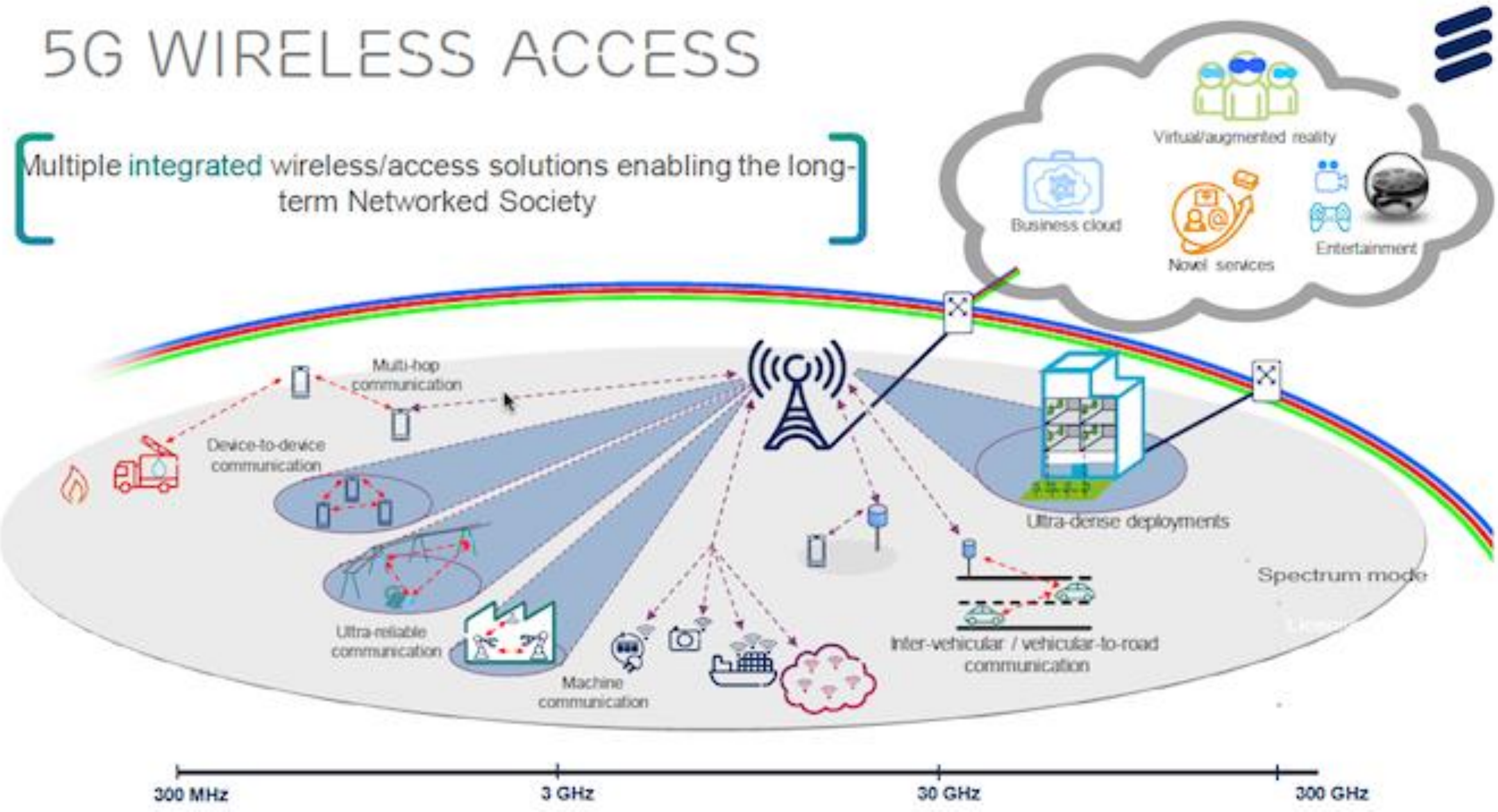
Large diversity of
Use cases & Requirements

Device-to-Device Communications

Car-to-Car Comm.

New requirements and characteristics due to communicating machines

Introduction



5G WIRELESS ACCESS

Multiple integrated wireless/access solutions enabling the long-term Networked Society

Virtual/augmented reality
Business cloud
Novel services
Entertainment
Multi-hop communication
Device-to-device communication
Ultra-reliable communication
Machine communication
Ultra-dense deployments
Inter-vehicular / vehicular-to-road communication
Spectrum mode
Licensed
300 MHz
3 GHz
30 GHz
300 GHz

Introduction

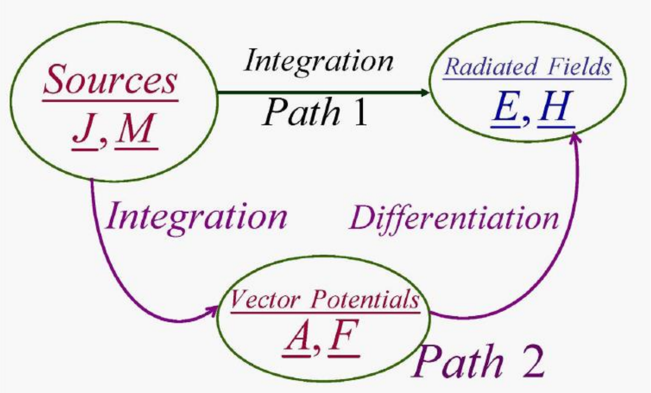
- Let us assume that only Electric source is present that will induce an Electric Current Density J thus the vector Magnetic Potential is given by

$$A = \frac{\mu}{4\pi} \iiint J \frac{e^{-jkr}}{R} dv'$$

$$H_A = \frac{1}{\mu} \nabla \times A$$

$$E_A = -j\omega A - j\frac{1}{\omega\mu\epsilon} \nabla(\nabla . A)$$

$$j\omega E_A + J = \nabla \times H_A$$


Sources
$\underline{J}, \underline{M}$
Integration
Path 1
Radiated Fields
$\underline{E}, \underline{H}$
Integration
Differentiation
Vector Potentials
$\underline{A}, \underline{F}$
Path 2

Field Transformation

- No closed form expression for the current density of printed antennas.
- No systematic or general guidelines are available for antenna designing.

TCM

- **Characteristic current Modes** for an arbitrary conducting object can be found.

$$[Z]I_n = (1 + j\lambda_n)[R]I_n$$

$$[X]I_n = \lambda_n[R]I_n$$

where, I_n represents the eigen vector and λ_n represents the eigen value, X represent the imaginary part while R represents the real part of the Z matrix.

- **Characteristic Modes** are find in the absence of the excitation source.
- **Characteristic modes** gain importance because of its important features:
  - ✓ The Modes obtained are real over the surface on which they exist.
  - ✓ Modes are orthogonal with each other.

[1] R. J. Garbacz, “A Generalized Expansion for Radiated and Scattered Fields,” Ph.D. dissertation, Ohio State University, 1968.
[2] R. F. Harrington and J. R. Mautz, “Theory of Characteristic Modes for Conducting Bodies,” IEEE Trans. Antennas Propagat., vol. AP-19, no. 5, pp. 622-628, Sept. 1971.
[3] M. Cabedo Fabrs, “Systematic design of antennas using the Theory of Characteristic Modes,” PhD. Dissertation, Universidad Politecnica de Valencia, Feb. 2007.
[4] Eva Antonino Daviu, "Analysis and Design of antennas for wireless communications using Modal Methods", PhD. Dissertation, Universidad Politecnica de Valencia, Feb.2008.

TCM

- **Eigen Value**

- In general, eigenvalues λ_n range from $-\infty$ to $+\infty$
- A mode is at resonance when its associated eigenvalue is zero.
- The sign of the eigenvalue determines whether the mode contributes to store magnetic energy (λn >0) or electric energy (λn <0).

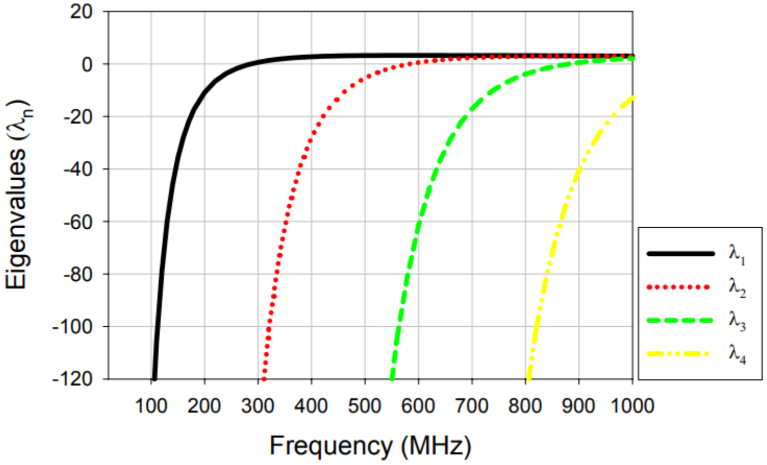


Figure: Eigen values associated with a wire dipole antenna having length of 0.5 m and wire diameter of 1 mm [3].

[3] M. Cabedo Fabrs, “Systematic design of antennas using the Theory of Characteristic Modes,” PhD. Dissertation, Universidad Politecnica de Valencia, Feb. 2007.

TCM

- **Modal Significance**

Modal Significance, is a measure of how significant a mode is for solving the EFIE at a given frequency. It also determines how hard or how easy it is to excite a mode.

$$MS_n = \left|\frac{1}{1+j\lambda_n}\right|$$

- Maximum value of modal significance is 1. This happens when the mode is externally resonant. Modal significance can decay to zero when the mode is not resonant
- Bandwidth of the mode can be found from the MS. for $\lambda_n = 1$, $\mathrm{MS} = 0.707$

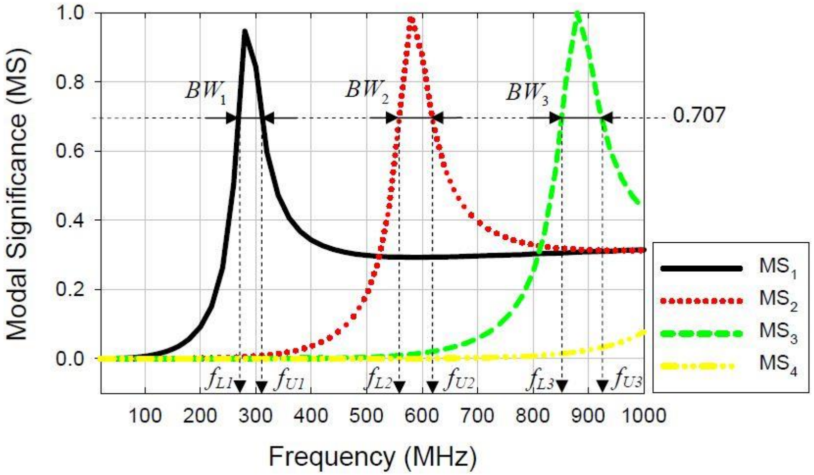


Figure: (a) MS and (b) CA for a wire dipole antenna having length of 100mm and wire diameter of 0.2mm [3].

[3] M. Cabedo Fabrs, “Systematic design of antennas using the Theory of Characteristic Modes,” PhD. Dissertation, Universidad Politecnica de Valencia, Feb. 2007.

TCM

- **Characteristic Angle**

Characteristic angle represent the phase lag between the electric field and surface current on a conductor.

$$\alpha_n = 180^o - tan^{-1}(\lambda_n)$$

- when α_n= 180 deg, the mode is externally resonant.
- when 90 deg < α_n < 180 deg, the mode is inductive.
- when 180 deg < α_n < 270 deg, the mode is capacitive.
- The f_u and f_L are obtained for the $\lambda_n = \pm 1$. The $\alpha_n = 225^o$ and $\alpha_n = 135^o$.

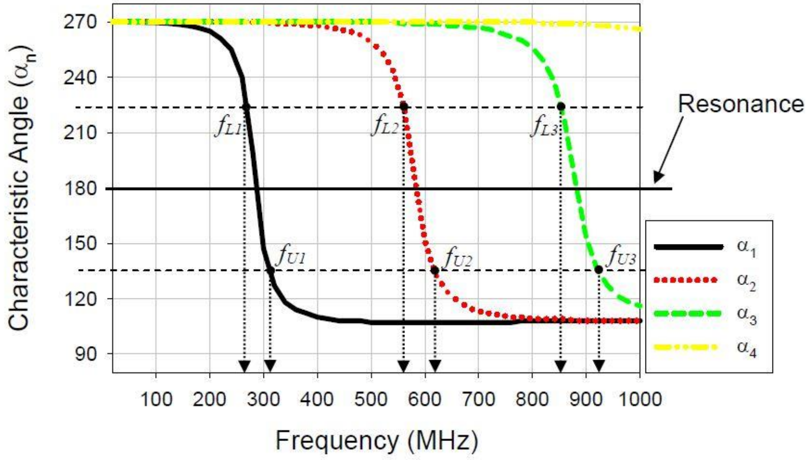


Figure: (a) MS and (b) CA for a wire dipole antenna having length of 100mm and wire diameter of 0.2mm [3].

[3] M. Cabedo Fabrs, “Systematic design of antennas using the Theory of Characteristic Modes,” PhD. Dissertation, Universidad Politecnica de Valencia, Feb. 2007.

TCM

- **Radiation Pattern**

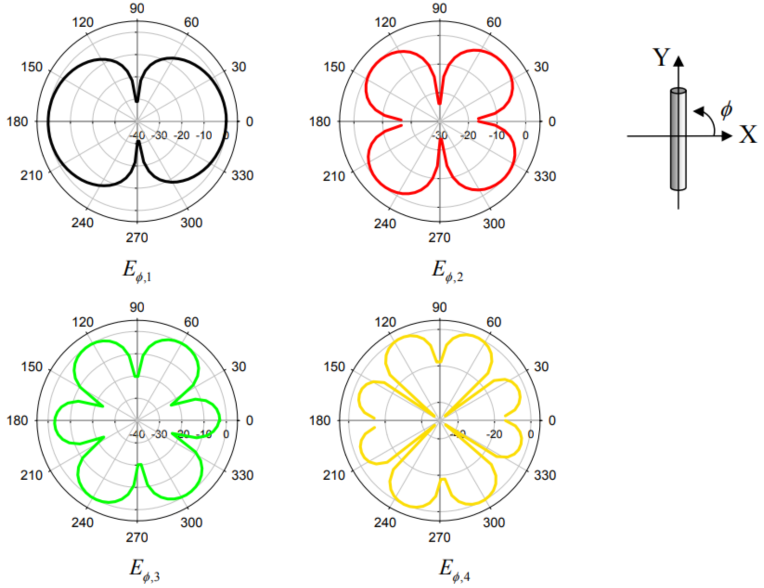
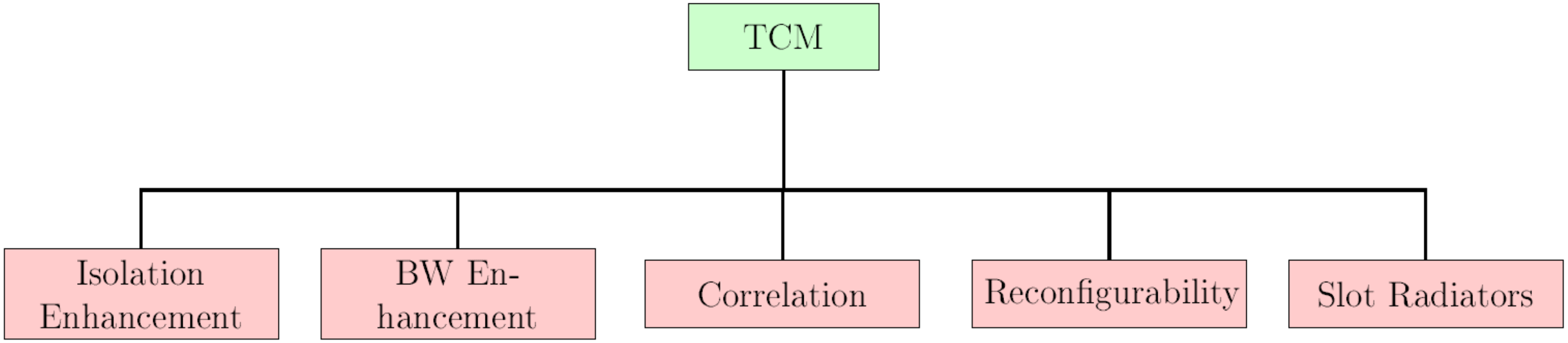


Figure: Azimuthal radiation pattern ($\theta = 90^o$) of the modal electric field produced by the first four characteristic modes of a dipole [3].

[3] M. Cabedo Fabrs, “Systematic design of antennas using the Theory of Characteristic Modes,” PhD. Dissertation, Universidad Politecnica de Valencia, Feb. 2007.

TCM Literature



TCM

Isolation Enhancement

BW Enhancement

Correlation

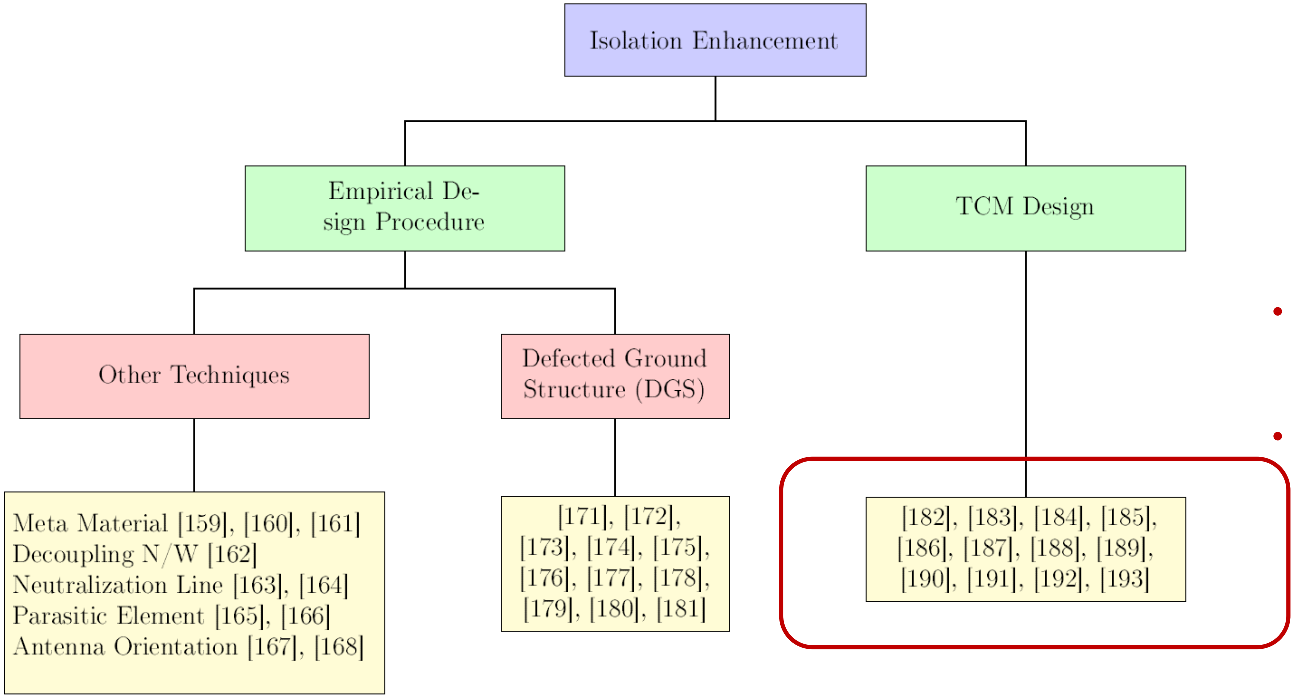
Reconfigurability

Slot Radiators

Beside these TCM Literature is extended to

- TCM Development
- TCM extended to Dielectric Resonator Antenna’s and Substrate.
- Massive MIMO
- Antenna in the presence of UAV or ship

Isolation Enhancement Using TCM



Isolation Enhancement

Empirical Design Procedure

TCM Design

Other Techniques

Defected Ground Structure (DGS)

Meta Material [159], [160], [161]
Decoupling N/W [162]
Neutralization Line [163], [164]
Parasitic Element [165], [166]
Antenna Orientation [167], [168]

[171], [172], [173], [174], [175], [176], [177], [178], [179], [180], [181]

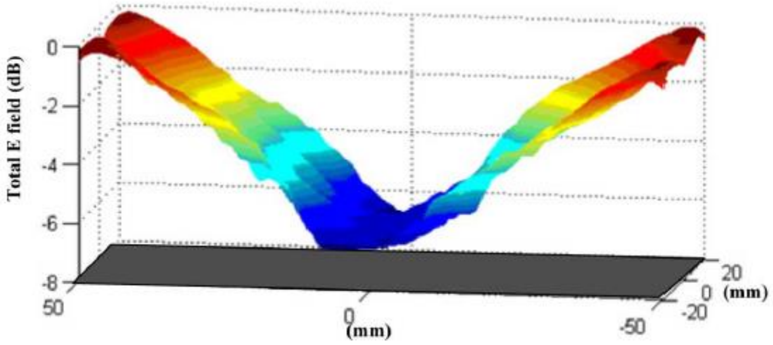
[182], [183], [184], [185], [186], [187], [188], [189], [190], [191], [192], [193]

- Study was limited to antenna placement on the chassis considering only one mode excitation < 1GHz.
- No other isolation enhancement was investigated.

[5] A. Ghalib, “Current Engineering methods applied to the design of MIMO antennas”, PhD Dissertation, King Fahd University of Petroleum and Minerals, Dammam, Saudi Arabia.

Isolation Enhancement Using TCM

- Chassis plays significant role in Isolation.
- The Best possible location for an antenna to effectively excite the chassis is the point of maximum Electric field.
- Different antenna geometries excite the chassis differently PIFA have more localized current as compared to Monopole.
- For Mode 1, the antennas located at the edge will excite the chassis effectively.
- In case of MIMO antenna will it be effective to place the antenna at the edges?
- What about placing antenna at edge and center?



Normalized magnitude of the total electric field of the first characteristic mode of the chassis at 1.35 GHz [6].

- Is placement of antenna at the center practical?
- More than one mode at 2 GHz?
- Electric field of mode 2 ?

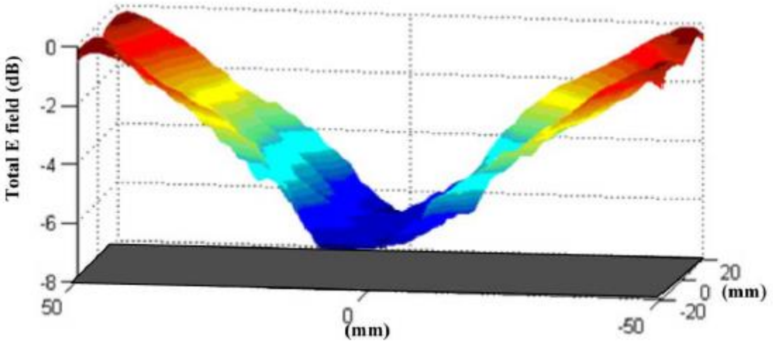
[6] H. Li, Y. Tan, B. K. Lau, Z. Ying and S. He, "Characteristic Mode Based Tradeoff Analysis of Antenna-Chassis Interactions for Multiple Antenna Terminals," in *IEEE Transactions on Antennas and Propagation*, vol. 60, no. 2, pp. 490-502, Feb. 2012.

[7] H. Li, B. K. Lau, Z. Ying and S. He, "Decoupling of Multiple Antennas in Terminals With Chassis Excitation Using Polarization Diversity, Angle Diversity and Current Control," in *IEEE Transactions on Antennas and Propagation*, vol. 60, no. 12, pp. 5947-5957, Dec. 2012.

[8] H. Li, Z. T. Miers and B. K. Lau, "Design of Orthogonal MIMO Handset Antennas Based on Characteristic Mode Manipulation at Frequency Bands Below 1 GHz," in *IEEE Transactions on Antennas and Propagation*, vol. 62, no. 5, pp. 2756-2766, May 2014.

Isolation Enhancement Using TCM

- Is placement of antenna at the center practical?
- More than one mode at 2 GHz?
- Electric field of mode 2 ?
- Can the current isolation technique predict whether the isolation can be enhanced or not?
- DGS, the shape and location matters



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[6] H. Li, Y. Tan, B. K. Lau, Z. Ying and S. He, "Characteristic Mode Based Tradeoff Analysis of Antenna-Chassis Interactions for Multiple Antenna Terminals," in *IEEE Transactions on Antennas and Propagation*, vol. 60, no. 2, pp. 490-502, Feb. 2012.

Isolation Enhancement Using TCM

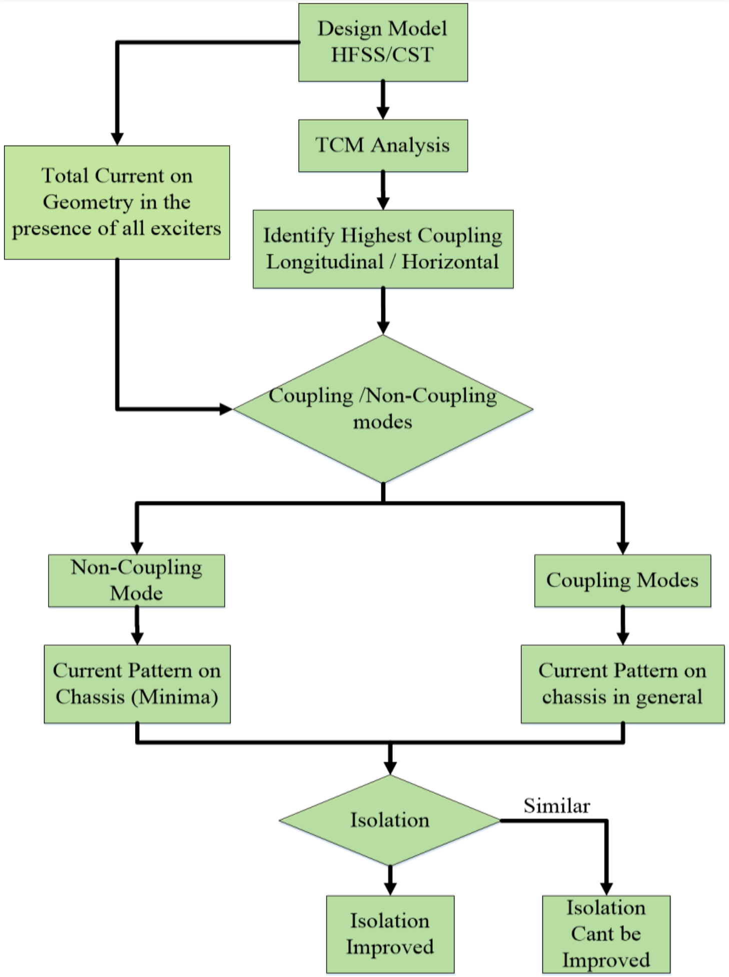
Developed a systematic approach that can predict whether a DGS can enhance the isolation between MIMO antenna elements or not. Provided a physical explanation to the physical behavior of DGS and explain its mechanism with the help of TCM

Isolation Enhancement Using TCM

Block Diagram of Proposed Method

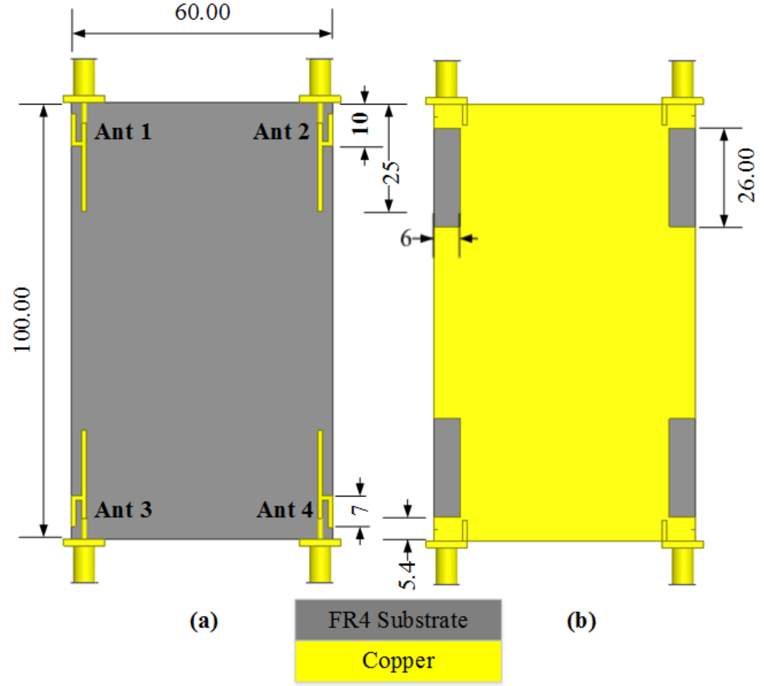
1. Perform TCM Analysis
2. Determine the total current on the surface of the antenna in the presence of all the exciters
3. Identify the coupling and non-coupling modes
4. Block the coupling modes without affecting the non-coupling modes.

Coupling modes: mode having such current distribution that couples the port currents of two antennas based on the locations of the antenna


Design Model HFSS/CST
TCM Analysis
Total Current on Geometry in the presence of all exciters
Identify Highest Coupling Longitudinal / Horizontal
Coupling /Non-Coupling modes
Non-Coupling Mode
Coupling Modes
Current Pattern on Chassis (Minima)
Current Pattern on chassis in general
Isolation
Similar
Isolation Improved
Isolation Cant be Improved

Isolation Enhancement Using TCM

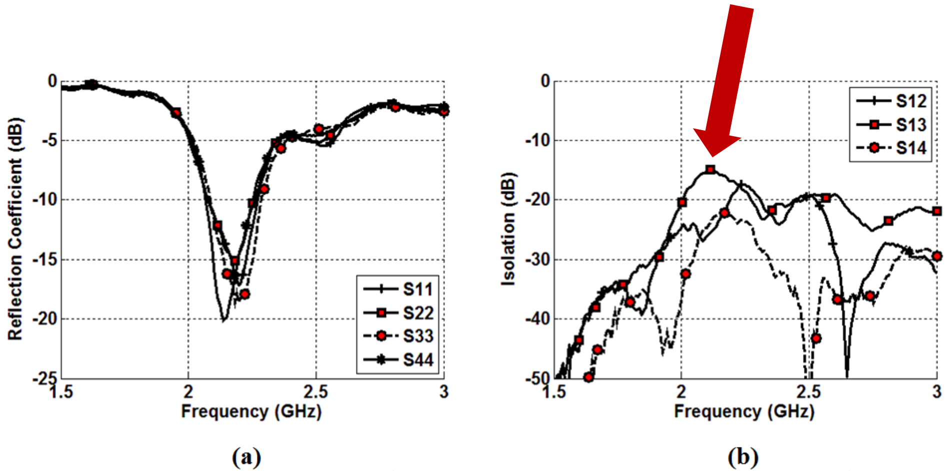
Design 1. 4-element MIMO PIFA design



Geometry of 4 elements PIFA (a) Top view, (b) Bottom view

FR4 Substrate, h=0.8mm
Dielectric constant=4.3
Size=100mmx60mm
Frequency BW=2.17-2.33 GHz
Gain=4.17 dB
Efficiency=97%

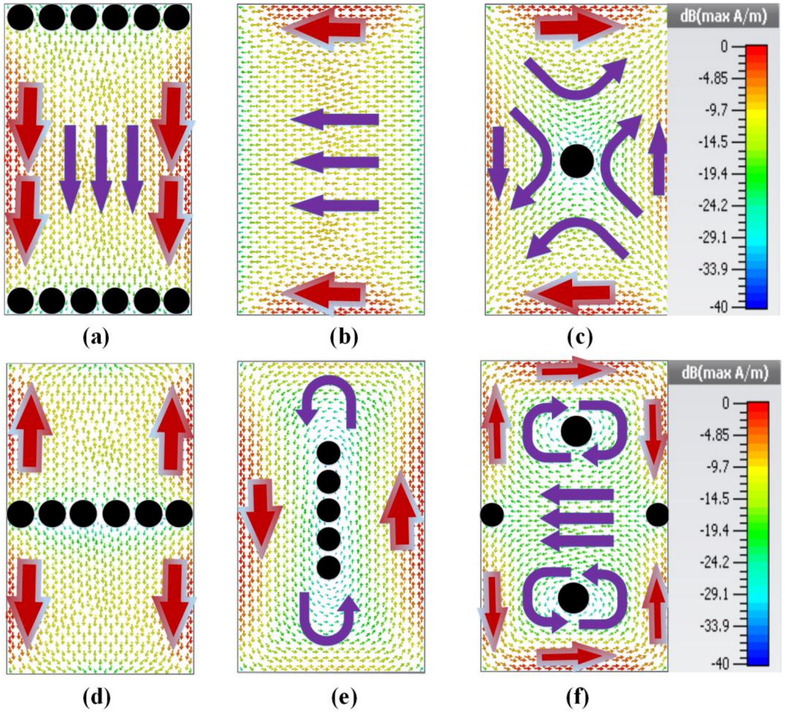
S12=-16.25 dB
S13=18.5 dB



Measured S parameters of 4 elements Monopole (a) Reflection coefficient (b) Isolation Curve

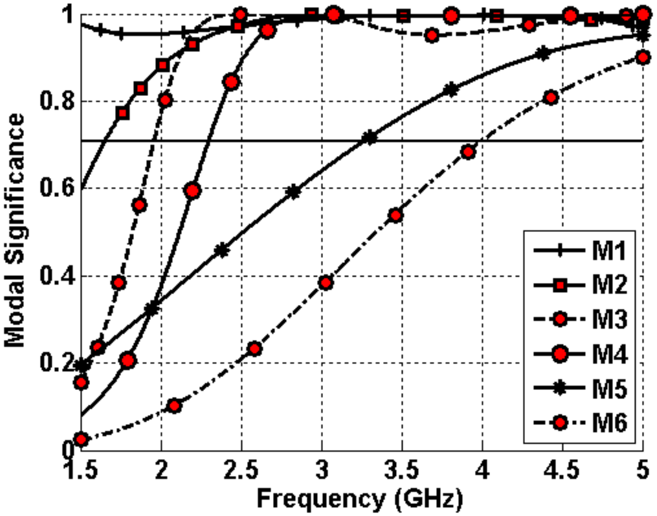
Isolation Enhancement Using TCM

Ground Plane



Current distribution of the first six modes of the chassis in the presence of an FR-4 substrate at 2.20 GHz

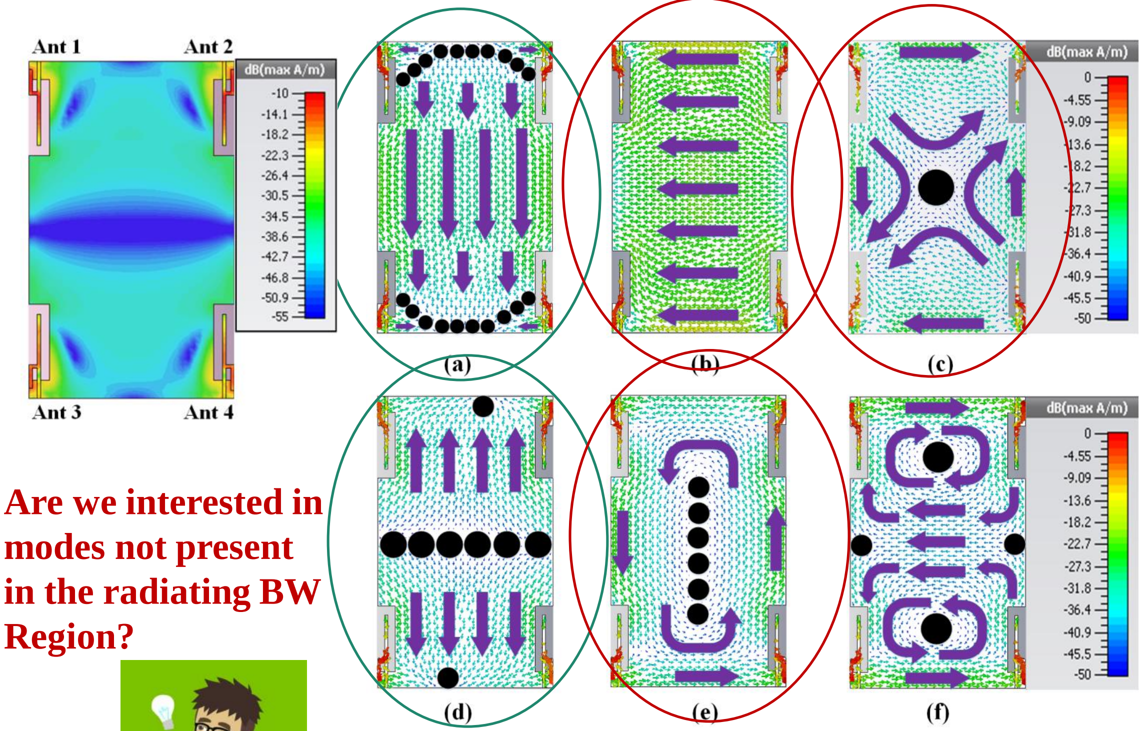
- The black spots represent current minima location. Red arrows show the current maxima location while the current direction is plotted by the violet arrow.



Modal Significance

Isolation Enhancement Using TCM

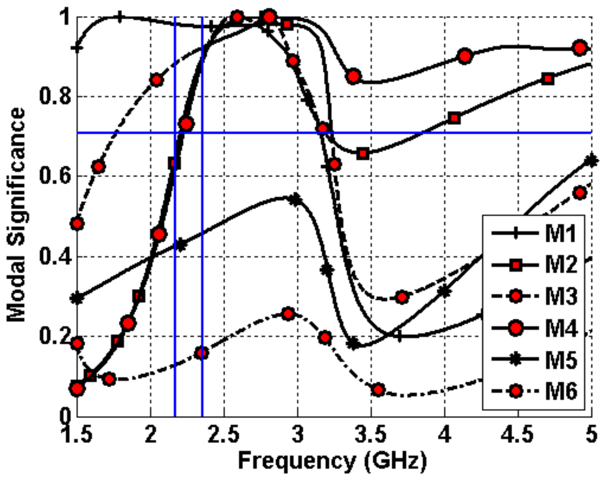
Design 1. 4-element MIMO PIFA Design


Ant 1
Ant 2
Ant 3
Ant 4
dB(max A/m)
-10
-14.1
-18.2
-22.3
-26.4
-30.5
-34.5
-38.6
-42.7
-46.8
-50.9
-55
dB(max A/m)
0
-4.55
-9.09
-13.6
-18.2
-22.7
-27.3
-31.8
-36.4
-40.9
-45.5
-50
(a)
(b)
(c)
(d)
(e)
(f)

Current distribution of the first six modes of the 4-element MIMO PIFA in the presence of an FR-4 substrate at 2.20 GHz

Are we interested in modes not present in the radiating BW Region?

- Mode 1 and 4 seems to be non-coupling modes.
- Mode 2 and 3 are excited with minimal affect. They are present in the radiating BW region
- **Stop Mode 3, Will it affect mode 1 and 4?**

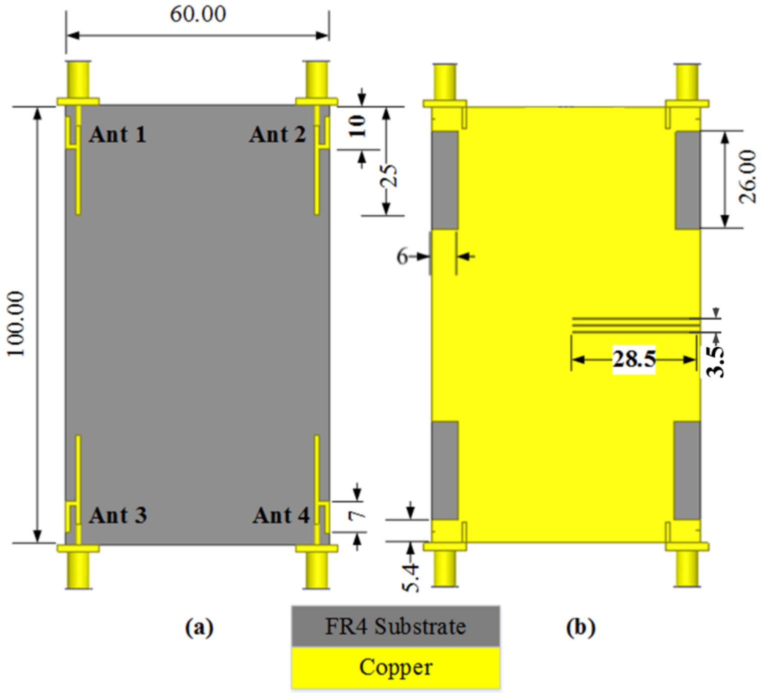


Modal Significance

- Chassis modes are affected because of the presence of the antenna
- Only 4 modes are present in the impedance BW region
- The blue line represent the impedance BW region

Isolation Enhancement Using TCM

Design 1. 4-element MIMO PIFA design including DGS


60.00
Ant 1
Ant 2
Ant 3
Ant 4
10
25
26.00
6
100.00
28.5
3.5
7
5.4
(a)
FR4 Substrate
Copper
(b)

Geometry of 4 elements PIFA including DGS
(a) Top view, (b) Bottom view

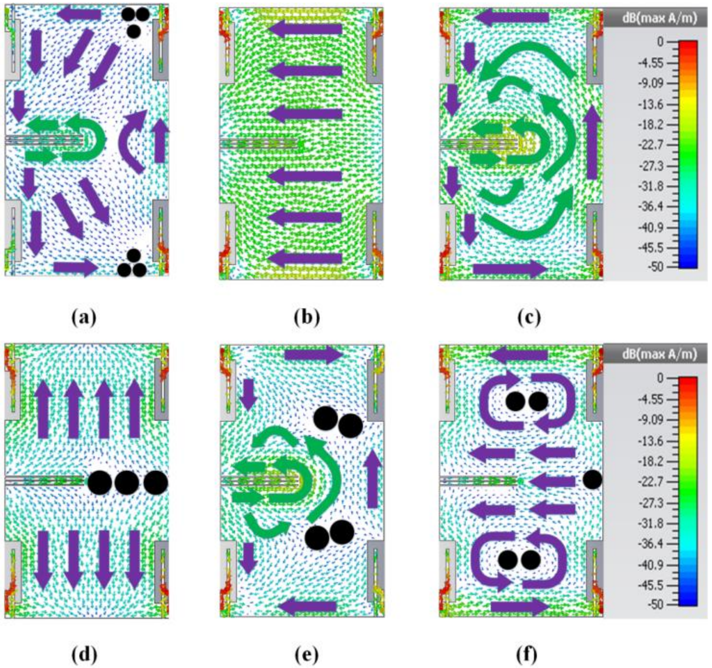
- A simple DGS consisting of 3 slit lines was introduced and optimized in Full wave solver.
- The isolation between Ant-1 and Ant-3 was enhanced by **12.75 dB.**
- **What happened? Let us investigate**

?

Isolation Enhancement Using TCM

Physical Explanation

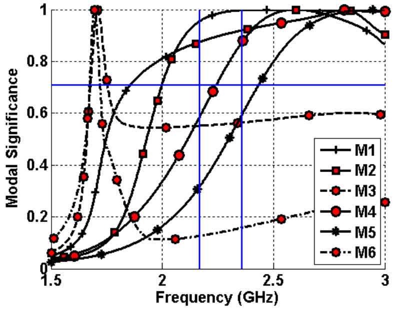
- DGS are producing currents in opposite direction to the modes current.
- Mode 3 **(coupling mode)** is no longer contributing in the desired impedance BW region. Stronger DGS currents are produced.
- Mode 5 currents are also blocked and Mode 6 is severely affected.
- Mode 2 is a coupling mode between Ant1- and Ant-2
- Mode 2 is not affected and Mode 1 current distribution is affected but the MS plots(radiating BW) is not that much affected


dB(max A/m)
0
-4.55
-9.09
-13.6
-18.2
-22.7
-27.3
-31.8
-36.4
-40.9
-45.5
-50

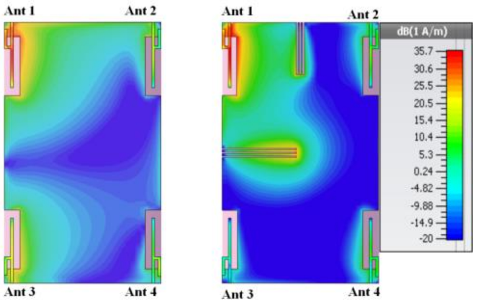
(a) (b) (c)

(d) (e) (f)

Current distribution of the first six modes of PIFA 4-element MIMO in the presence of single DGS at 2.20 GHz



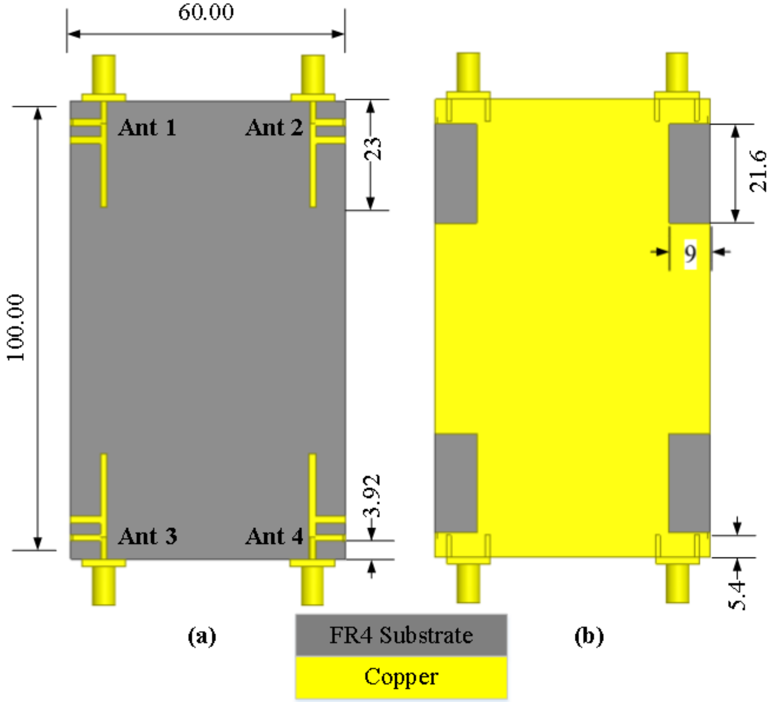
Modal Significance


Ant 1
Ant 2
Ant 3
Ant 4
Ant 1
Ant 2
Ant 3
Ant 4
dB(1 A/m)
35.7
30.6
25.5
20.5
15.4
10.4
5.3
0.24
-4.82
-9.88
-14.9
-20

A. How can we enhance the Isolation between Ant-1 and Ant-2
B. Does the Isolation enhancement b/w Ant-1 and Ant-3 enhances isolation enhancement b/w Ant-2 and Ant-4

Isolation Enhancement Using TCM

Design 2. 4-element MIMO Monopole design

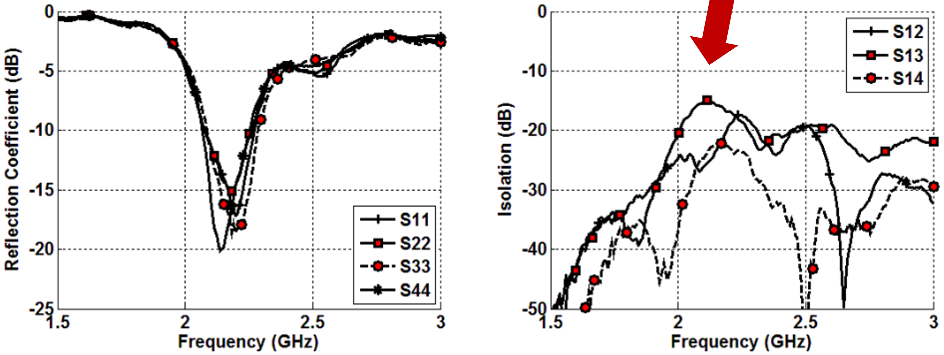


Geometry of 4 elements Monopole (a) Top view, (b) Bottom view

Let us investigate a case when the isolation cannot be improved

FR4 Substrate, h=0.8mm
Dielectric constant=4.3
Size=100mmx60mm
Frequency=2.13-2.6 GHz
BW=136 MHz
Gain=3.34 dB
Efficiency=80%

S12=-15.5 dB
S13=17.3 dB



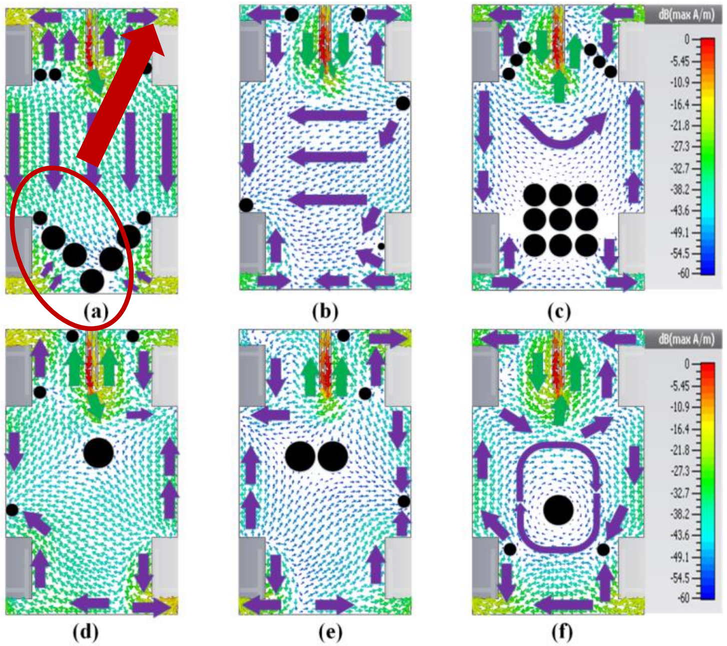
(a) (b)

Measured S parameters of 4 elements Monopole (a) Reflection coefficient (b) Isolation Curve

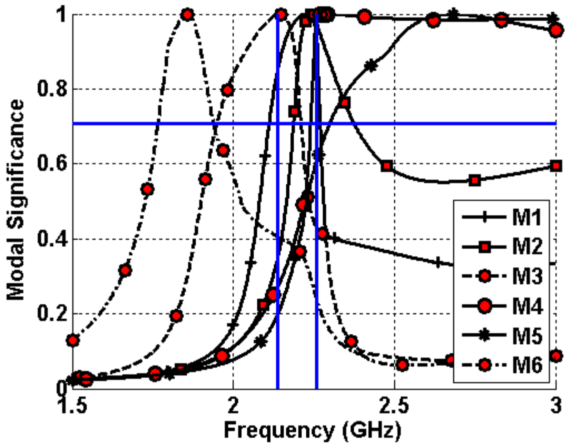
Isolation Enhancement Using TCM

A. Placing a DGS at this location will isolate the antennas. NOT ACCEPTABLE….
B. Stopping mode 3 or 2 in this case will strongly affect mode 1.

- Isolation between Antennas on the shorter edge is already enhanced.
- Mode 1 is the only mode that is having the same radiating BW as the impedance BW of the antenna.
- Mode 3 contribution to the radiating BW ends in the middle of the impedance BW.
- Mode 2 starts contribution in the middle of the impedance BW to the radiating BW.
- The effective mode is mode 1. In this case we have only one mode as the main contributor and there is no possible location.

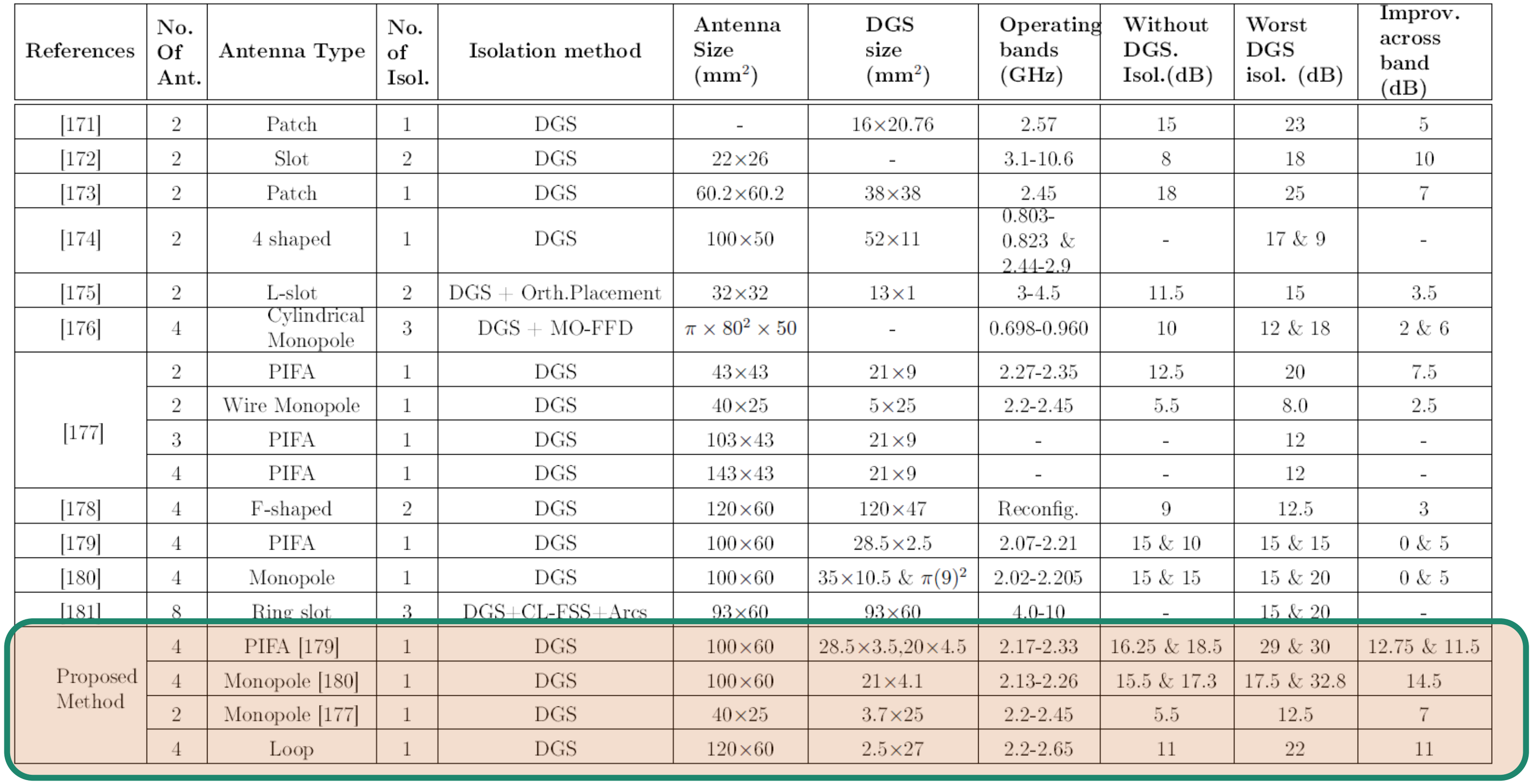


Current distribution of the first six modes of Monopole 4-element MIMO in the presence of single DGS at 2.20 GHz



Modal Significance

Isolation Enhancement Using TCM

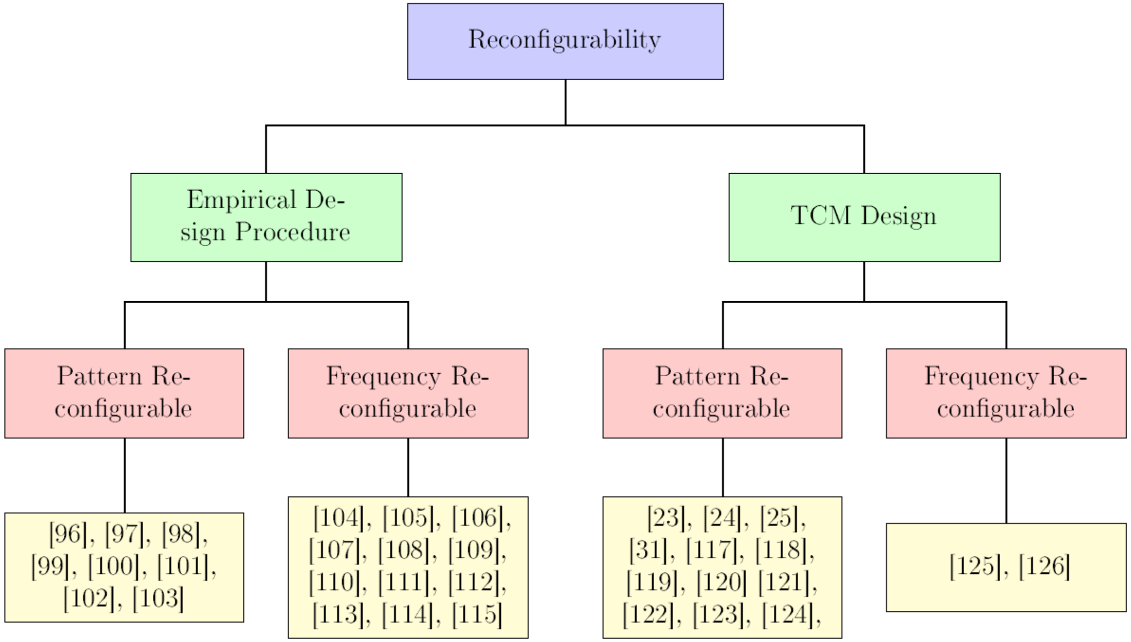


References	No. Of Ant.	Antenna Type	No. of Isol.	Isolation method	Antenna Size (mm^2)	DGS size (mm^2)	Operating bands (GHz)	Without DGS. Isol.(dB)	Worst DGS isol. (dB)	Improv. across band (dB)
[171]	2	Patch	1	DGS	-	16×20.76	2.57	15	23	5
[172]	2	Slot	2	DGS	22×26	-	3.1-10.6	8	18	10
[173]	2	Patch	1	DGS	60.2×60.2	38×38	2.45	18	25	7
[174]	2	4 shaped	1	DGS	100×50	52×11	0.803-0.823 & 2.44-2.9	-	17 & 9	-
[175]	2	L-slot	2	DGS + Orth.Placement	32×32	13×1	3-4.5	11.5	15	3.5
[176]	4	Cylindrical Monopole	3	DGS + MO-FFD	$\pi \times 80^2 \times 50$	-	0.698-0.960	10	12 & 18	2 & 6
[177]	2	PIFA	1	DGS	43×43	21×9	2.27-2.35	12.5	20	7.5
	2	Wire Monopole	1	DGS	40×25	5×25	2.2-2.45	5.5	8.0	2.5
	3	PIFA	1	DGS	103×43	21×9	-	-	12	-
	4	PIFA	1	DGS	143×43	21×9	-	-	12	-
[178]	4	F-shaped	2	DGS	120×60	120×47	Reconfig.	9	12.5	3
[179]	4	PIFA	1	DGS	100×60	28.5×2.5	2.07-2.21	15 & 10	15 & 15	0 & 5
[180]	4	Monopole	1	DGS	100×60	35×10.5 & $\pi(9)^2$	2.02-2.205	15 & 15	15 & 20	0 & 5
[181]	8	Ring slot	3	DGS+CL-FSS+Arcs	93×60	93×60	4.0-10	-	15 & 20	-
Proposed Method	4	PIFA [179]	1	DGS	100×60	28.5×3.5,20×4.5	2.17-2.33	16.25 & 18.5	29 & 30	12.75 & 11.5
	4	Monopole [180]	1	DGS	100×60	21×4.1	2.13-2.26	15.5 & 17.3	17.5 & 32.8	14.5
	2	Monopole [177]	1	DGS	40×25	3.7×25	2.2-2.45	5.5	12.5	7
	4	Loop	1	DGS	120×60	2.5×27	2.2-2.65	11	22	11

[5] A. Ghalib, “Current Engineering methods applied to the design of MIMO antennas”, PhD Dissertation, King Fahd University of Petroleum and Minerals, Dammam, Saudi Arabia.

[9] A. Ghalib and M. S. Sharawi, "TCM Analysis of Defected Ground Structures for MIMO Antenna Designs in Mobile Terminals," in *IEEE Access*, vol. 5, pp. 19680-19692, 2017. doi: 10.1109/ACCESS.2017.2739419

Reconfigurability Using TCM

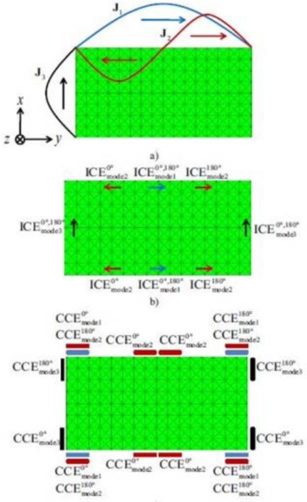


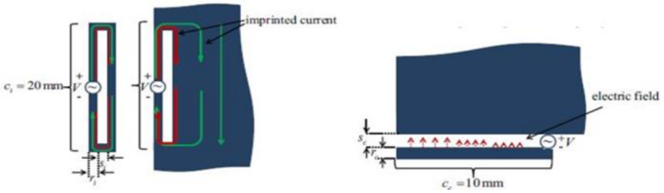
- Reconfigurability
  - Empirical Design Procedure
    - Pattern Reconfigurable
      - [96], [97], [98], [99], [100], [101], [102], [103]
    - Frequency Reconfigurable
      - [104], [105], [106], [107], [108], [109], [110], [111], [112], [113], [114], [115]
  - TCM Design
    - Pattern Reconfigurable
      - [23], [24], [25], [31], [117], [118], [119], [120] [121], [122], [123], [124],
    - Frequency Reconfigurable
      - [125], [126]

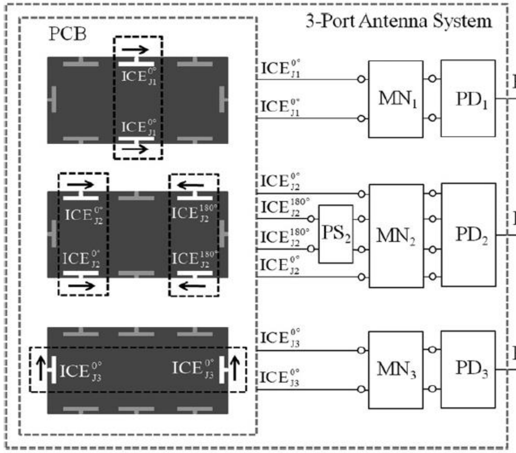
[5] A. Ghalib, “Current Engineering methods applied to the design of MIMO antennas”, PhD Dissertation, King Fahd University of Petroleum and Minerals, Dammam, Saudi Arabia.

Pattern Reconfigurability Using TCM

- **Pattern Reconfigurable & Complex Feed [8]**


J_1
J_2
J_3
x
y
z
a)
b)
ICE
CCE


imprinted current
$c_i = 20$ mm
V
electric field
$c_o = 10$ mm

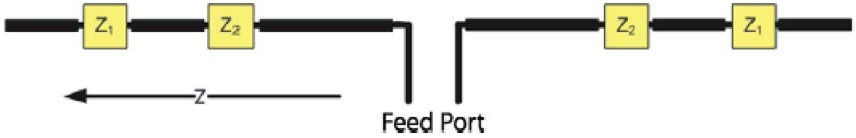

PCB
3-Port Antenna System
$ICE^{0°}_{J1}$
$ICE^{0°}_{J2}$
$ICE^{180°}_{J2}$
$ICE^{0°}_{J3}$
PS_2
MN_1
MN_2
MN_3
PD_1
PD_2
PD_3
Port 1
Port 2
Port 3

[10] R. Martens and D. Manteufel, "Systematic design method of a mobile multiple antenna system using the theory of characteristic modes," IET Microwaves Antennas & Propagation, vol. 8, no. 12, pp. 887-893, Sept. 2014.

[11] K. K. Kishor and S. V. Hum, "A pattern reconfigurable chassis-mode MIMO antenna," IEEE Transactions on Antennas and Propagation, vol. 62, no. 6, pp. 32903298, June 2014.

Frequency Reconfigurability Using TCM

- **Frequency Reconfigurable & Reactive Load for BW Enhancement**
  - ✓ General Current Pattern of Basic antennas is known.
  - ✓ To resonate antenna at distinct frequency, Some constraints shall be followed like the antenna electrical length, impedance matching.
  - ✓ One constraint is that the current pattern shall be same like
    - ➢ $\frac{\lambda}{2}$ dipole at 1 GHz.
    - ➢ $\frac{\lambda}{2}$ dipole at 2GHz.
  - ✓ From the desired current pattern, we can calculate



- **Shortcomings**
  - ✓ No direct Implication of TCM. No use of Modal Behavior.
  - ✓ The Number of Reactance needed as well as the placement of the Reactance was empirical.

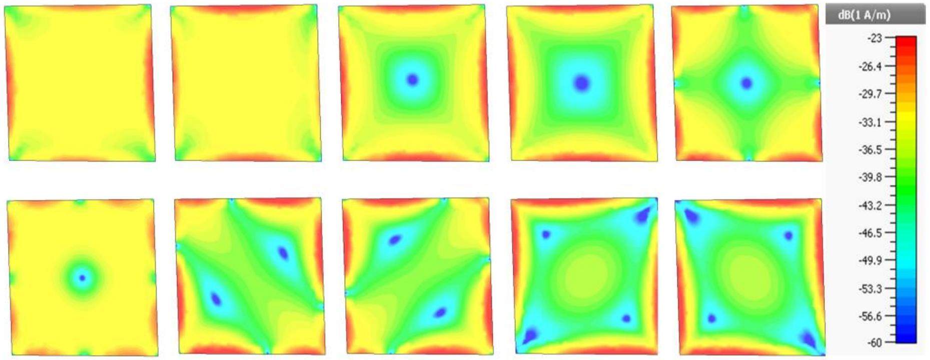
[12] K. A. Obeidat, B. D. Raines, R. G. Rojas and B. T. Strojny, “Design of Frequency Reconfigurable Antennas Using the Theory of Characteristic Modes,” IEEE Transactions on Antennas and Propagation, vol. 58, no. 10, pp. 3106-3113, Oct. 2010.
[13] K. A. Obeidat, B. D. Raines and R. G. Rojas, “Antenna design and analysis using characteristic modes,” IEEE Antennas and Propagation Society International Symposium, pp. 5993-5996,2007.

Frequency Reconfigurability Using TCM

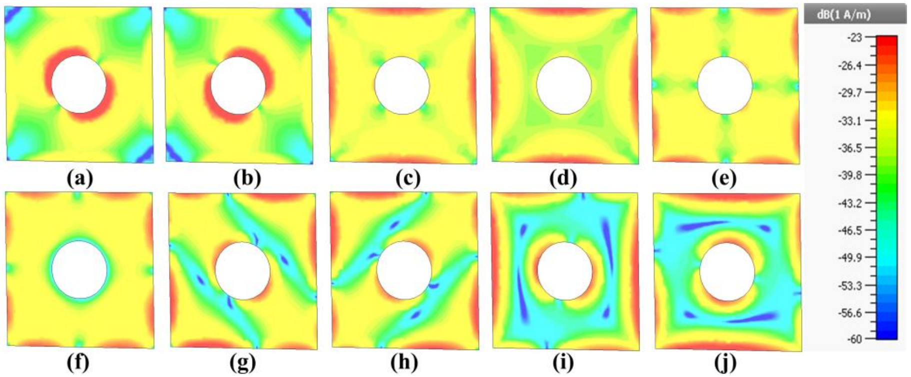
Investigated the appearance of slot mode in slot antennas. A suitable MIMO circular slot antenna design covering frequency Band from 1.8 to 2.45 GHz having frequency reconfigurable behavior is presented. Physical mechanism of frequency reconfigurability from the perspective of TCM is also investigated.

Slot Mode TCM Analysis

- Chassis size of 80x80 mm^2 is considered
- A circular slot of radius 15 mm was introduced at the center of the chassis.
- Are new slot modes generated?
- Observe mode 1 and 2
- What happened to the chassis modes 1 and 2?
- The MS curves of mode 1 and 2 of the chassis and the mode 1 and 2 in the presence of the slot are resembling?

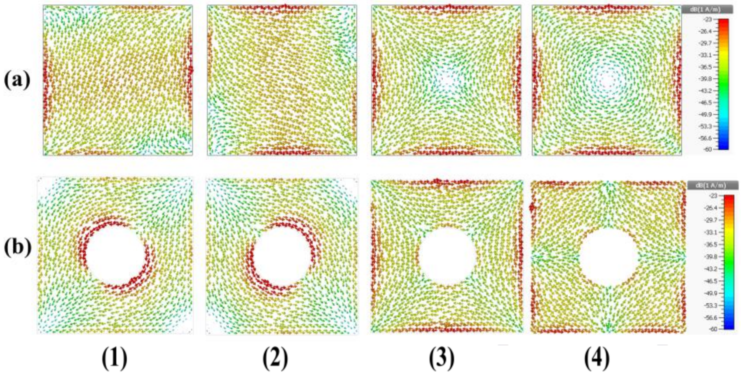


Current distribution of the first 10 modes of the chassis

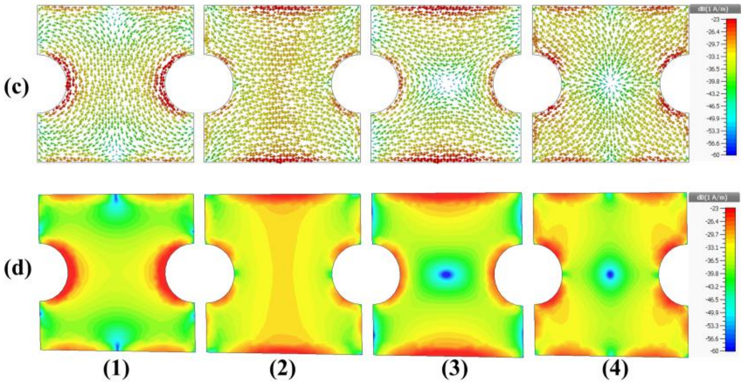


Current distribution of the first 10 modes of a circular slot of radiu
15 mm at the center of the chassis

Slot Mode TCM Analysis



(1)-(4) represents the first four modes of (a) Chassis (b) Circular slot of radius 15 mm at center of chassis

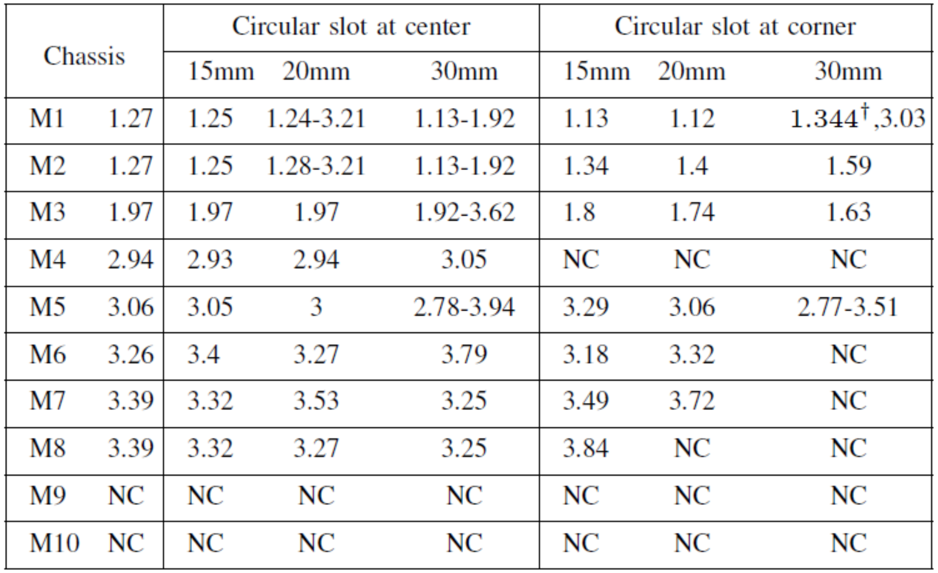


(c) Circular slot of radius 15 mm at both edges of chassis
(d) Circular slot of radius 15 mm at both edges of chassis with continuous current flow.

- Mode 1 and 2 current are flowing on the center while the other modes are having null that’s why mode 3 to 10 are not affected
- The new current maxima across the slot is due to current flow direction of mode 1 and 2
- **What about the size of the slot? Will it affect more modes?**
- **Will always be only these two modes affected?**

Slot Mode TCM Analysis

- Center case, circular slot of radius 15 mm, none of the chassis mode is affected in terms of radiating BW.
- We have got current maxima across the slot
- Center case, circular slot of radius 30 mm, M1 to M3 and M5 and M6 are significantly affected.
- **Size Matters**
- Edge case, circular slot of 15 mm M4 is significantly affected.
- **Location matters**



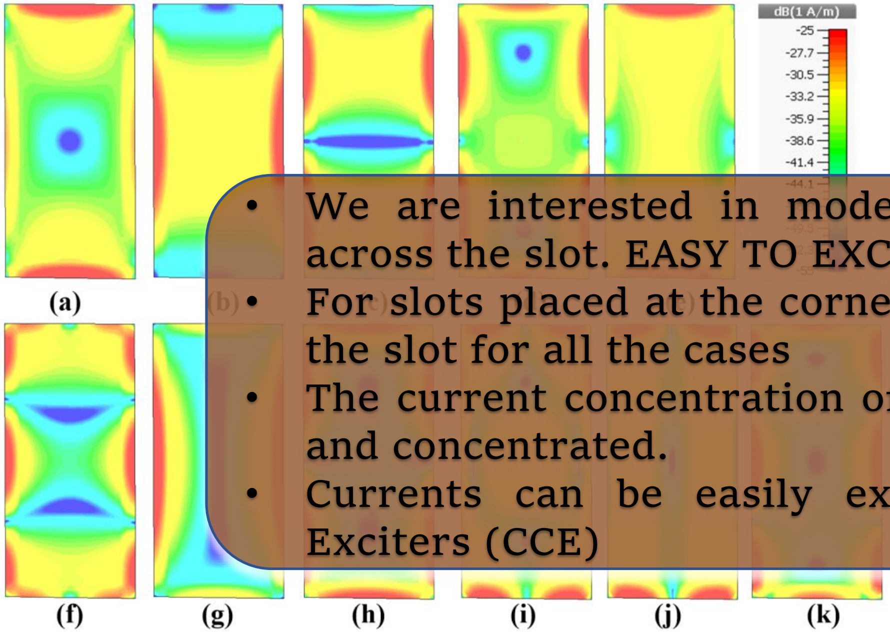
Chassis		Circular slot at center			Circular slot at corner		
		15mm	20mm	30mm	15mm	20mm	30mm
M1	1.27	1.25	1.24-3.21	1.13-1.92	1.13	1.12	$1.344^{\dagger}$,3.03
M2	1.27	1.25	1.28-3.21	1.13-1.92	1.34	1.4	1.59
M3	1.97	1.97	1.97	1.92-3.62	1.8	1.74	1.63
M4	2.94	2.93	2.94	3.05	NC	NC	NC
M5	3.06	3.05	3	2.78-3.94	3.29	3.06	2.77-3.51
M6	3.26	3.4	3.27	3.79	3.18	3.32	NC
M7	3.39	3.32	3.53	3.25	3.49	3.72	NC
M8	3.39	3.32	3.27	3.25	3.84	NC	NC
M9	NC	NC	NC	NC	NC	NC	NC
M10	NC	NC	NC	NC	NC	NC	NC

Slot Shape Effects on Chassis Modes

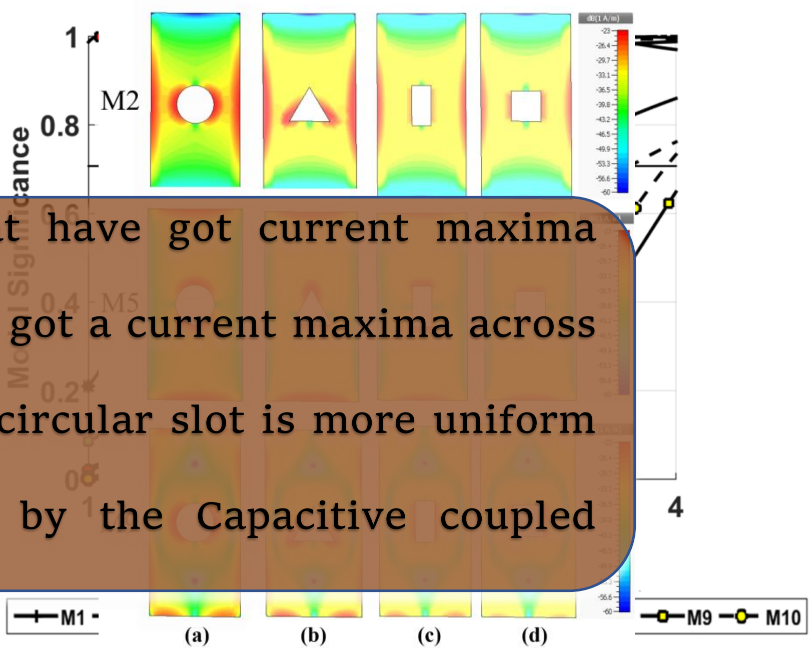
Chassis Modes

A. Mode-2, 5 and 9 are affected.
B. Other Modes have current minima's at the location

- We are interested in modes that have got current maxima across the slot. EASY TO EXCITE
- For slots placed at the corner, we got a current maxima across the slot for all the cases
- The current concentration of the circular slot is more uniform and concentrated.
- Currents can be easily excited by the Capacitive coupled Exciters (CCE)

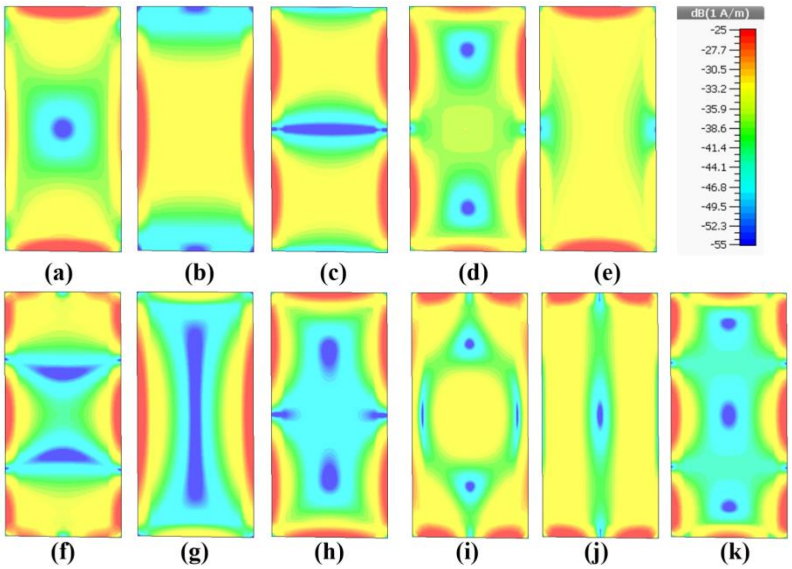


Current distribution of the first 11 modes of the chassis, where, (a)-(k) represents Mode 1 to Mode 11.

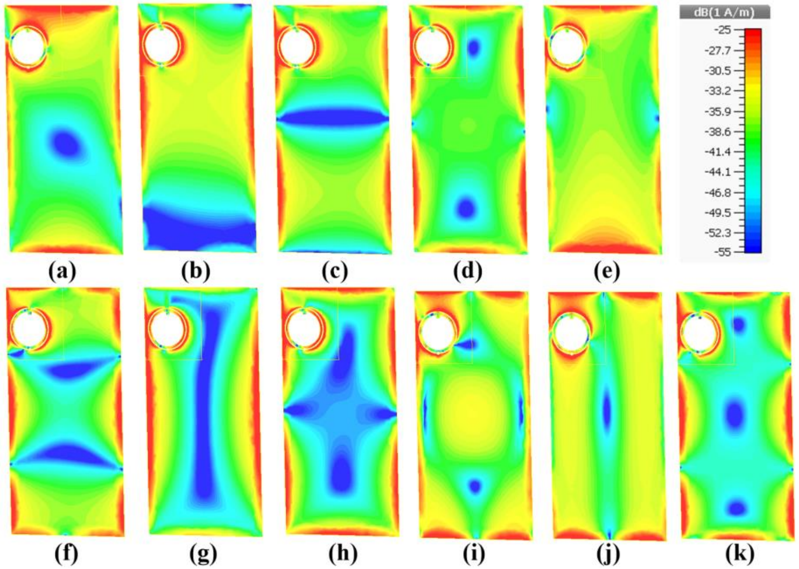


The rows represent mode 2, 5 and 9 respectively, where (a) Circular slot (b) Triangular slot (c) Rectangular slot (d) Square slot.

Circular Slot (Single/ MIMO) TCM Analysis



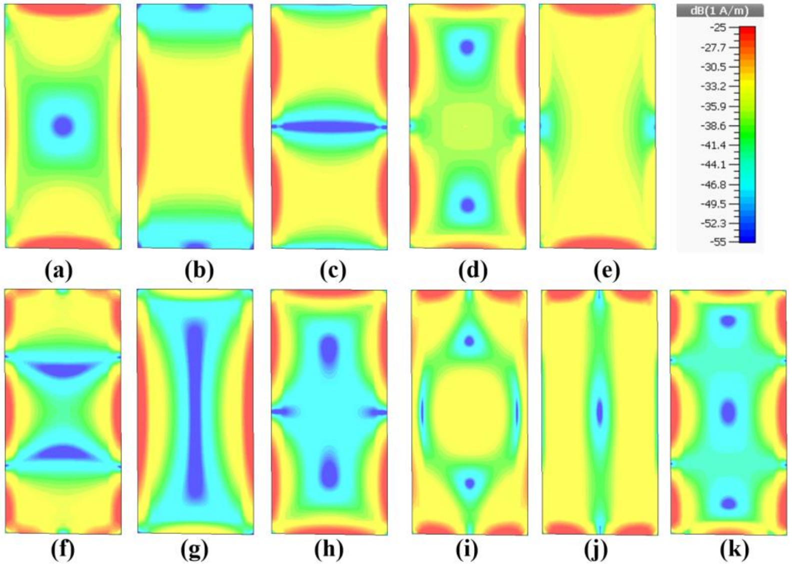
Current distribution of the first 11 modes of the chassis, where, (a)-(k) represents Mode 1 to Mode 11.



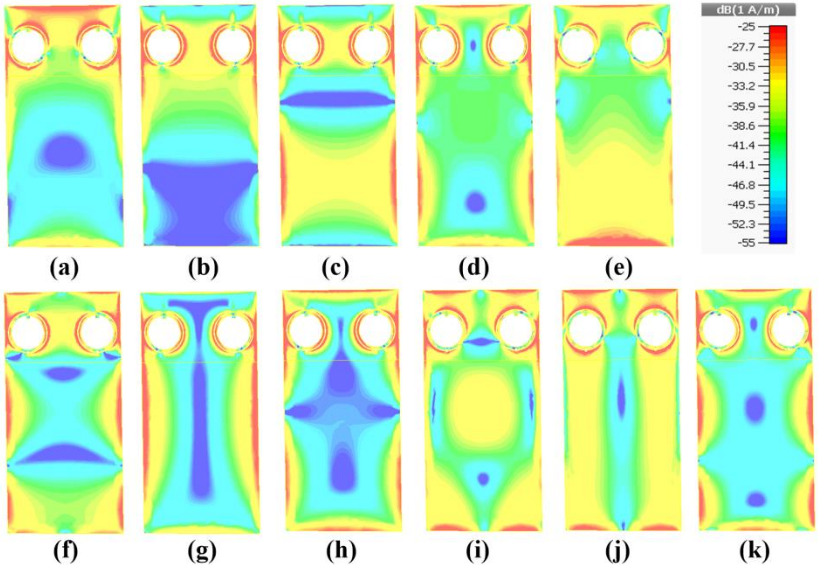
Current distribution of the first 11 modes of single circular slot antenna when introduced in the chassis, where, (a)-(k) represents Mode 1 to Mode 11.

A. All the modes have current maxima across the slot. IS IT GOOD
B. Mode 2 current null seems to be enhanced

Circular Slot (Single/ MIMO) TCM Analysis


dB(1 A/m)
-25
-27.7
-30.5
-33.2
-35.9
-38.6
-41.4
-44.1
-46.8
-49.5
-52.3
-55
(a)
(b)
(c)
(d)
(e)
(f)
(g)
(h)
(i)
(j)
(k)

Current distribution of the first 11 modes of the chassis, where, (a)-(k) represents Mode 1 to Mode 11.


dB(1 A/m)
-25
-27.7
-30.5
-33.2
-35.9
-38.6
-41.4
-44.1
-46.8
-49.5
-52.3
-55
(a)
(b)
(c)
(d)
(e)
(f)
(g)
(h)
(i)
(j)
(k)

Current distribution of the first 11 modes of 2-element circular slot antenna when introduced in the chassis, where, (a)-(k) represents Mode 1 to Mode 11.

A. All the modes have current maxima across the slot. IS IT GOOD
B. Mode 2 current is AFFECTED
C. Mode 1 and 3 are slightly affected

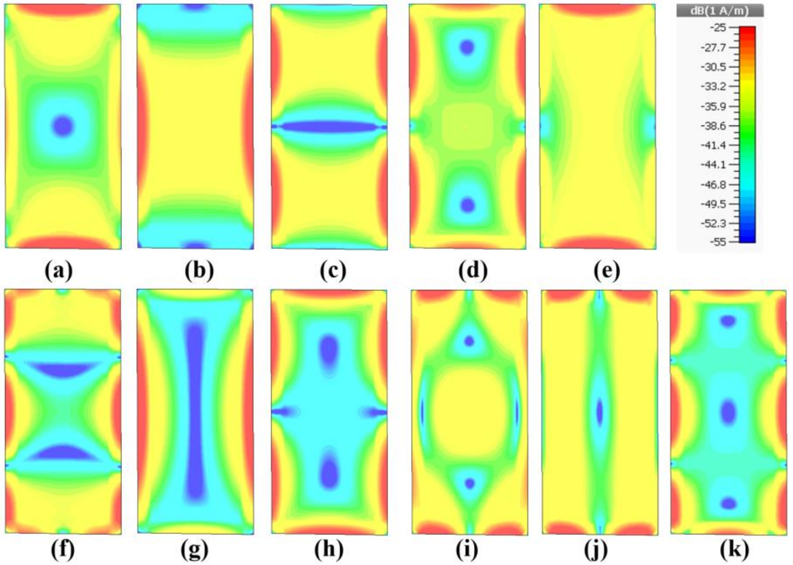
Circular Slot (Single/ MIMO) TCM Analysis

- What do you think of 4-element circular MIMO Slot case.

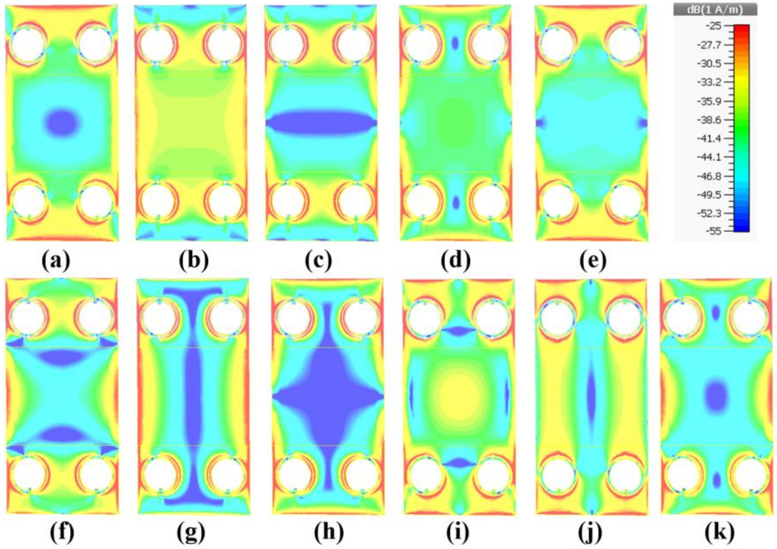
GREATLY AFFECTED

?

Circular Slot (Single/ MIMO) TCM Analysis



Current distribution of the first 11 modes of the chassis, where, (a)-(k) represents Mode 1 to Mode 11.



Current distribution of the first 11 modes of 4-element circular slot antenna when introduced in the chassis, where, (a)-(k) represents Mode 1 to Mode 11.

A. The currents are concentrated across the slot. IS IT GOOD
B. The symmetrical nature of the slots does not alter the current distribution of the chassis modes
C. The radiating BW of the chassis and 4-element slot case was the least affected

Circular Slot (Single/ MIMO) TCM Analysis

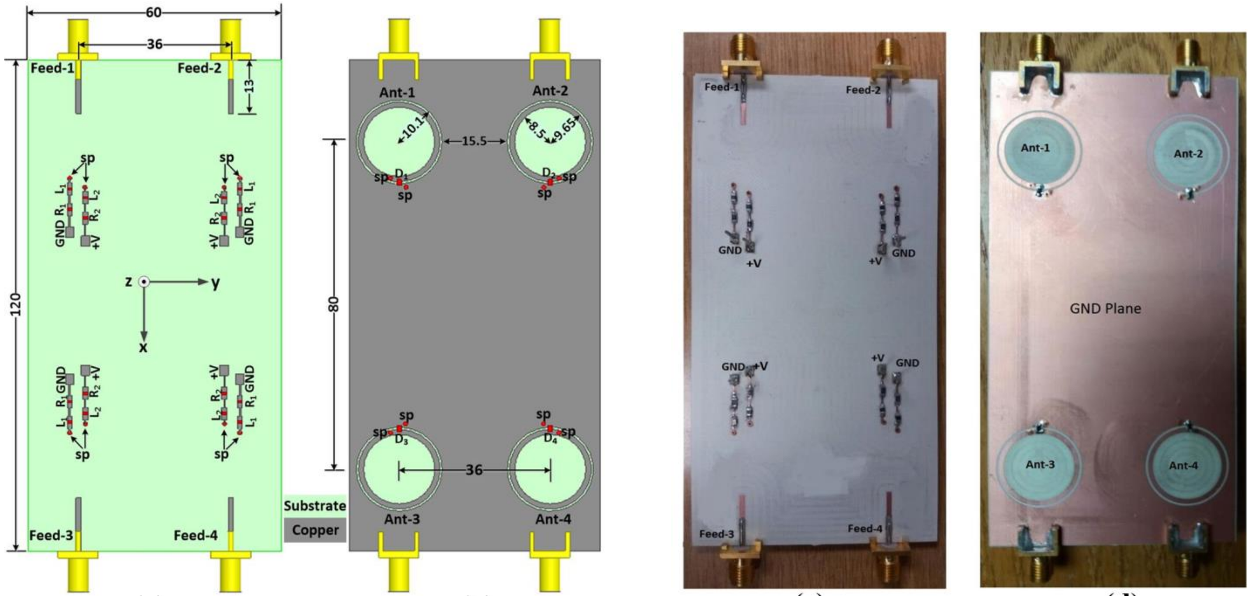
A. The presence of the current maxima across the Slot. IS IT GOOD
B. We want the excitation of a single mode
C. The excitation of more than one mode creates antiresonance because of the transitions between the modes
D. WE DO NOT WANT IT

Proposed Design

4-element MIMO Circular loop antenna

Design Features:

- Rogers RO4350 substrate
- Dielectric constant of 3.8
- Capacitance was varied between 0.84 pF to 5.08 pF
- BW 1.8 GHz to 2.45 GHz
- Each Band having at least 40 MHz
- Wide spacing at the center for possible placement of the battery


60
36
Feed-1
Feed-2
13
sp
L1
R1
L2
R2
GND
+V
z
y
x
120
Feed-3
Feed-4
Substrate
Copper
Ant-1
Ant-2
10.1
15.5
8.5
9.65
D1
D2
80
36
D3
D4
Ant-3
Ant-4
GND Plane

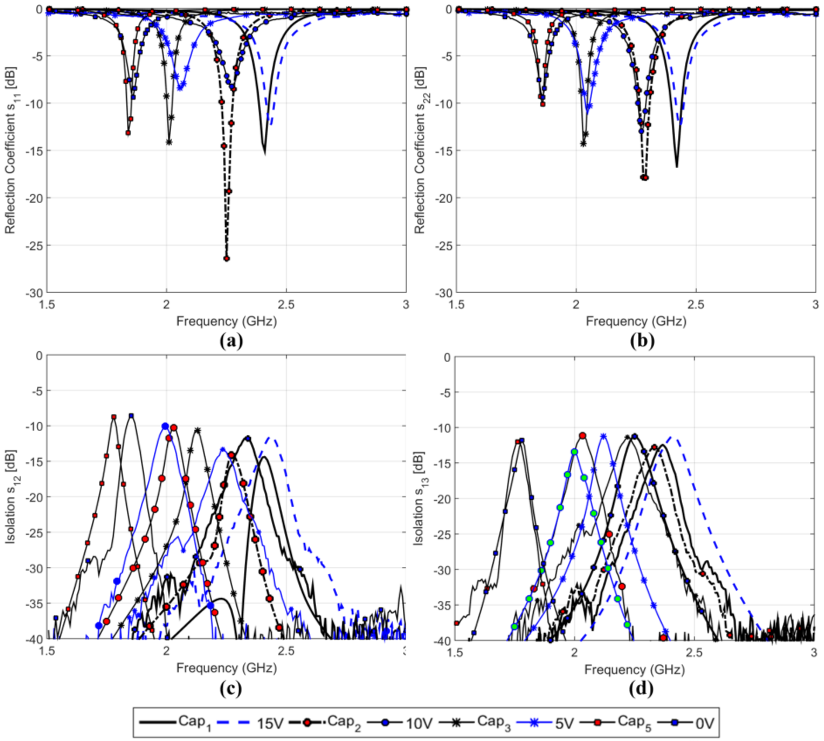
Circular slot MIMO design where, (a) Top Layer, (b) Ground plane, (c) Fabricated prototype top layer, (d) Fabricated prototype Ground layer. All dimensions are in millimeter (mm).

Annular ring was introduced for reconfigurability

Proposed Design

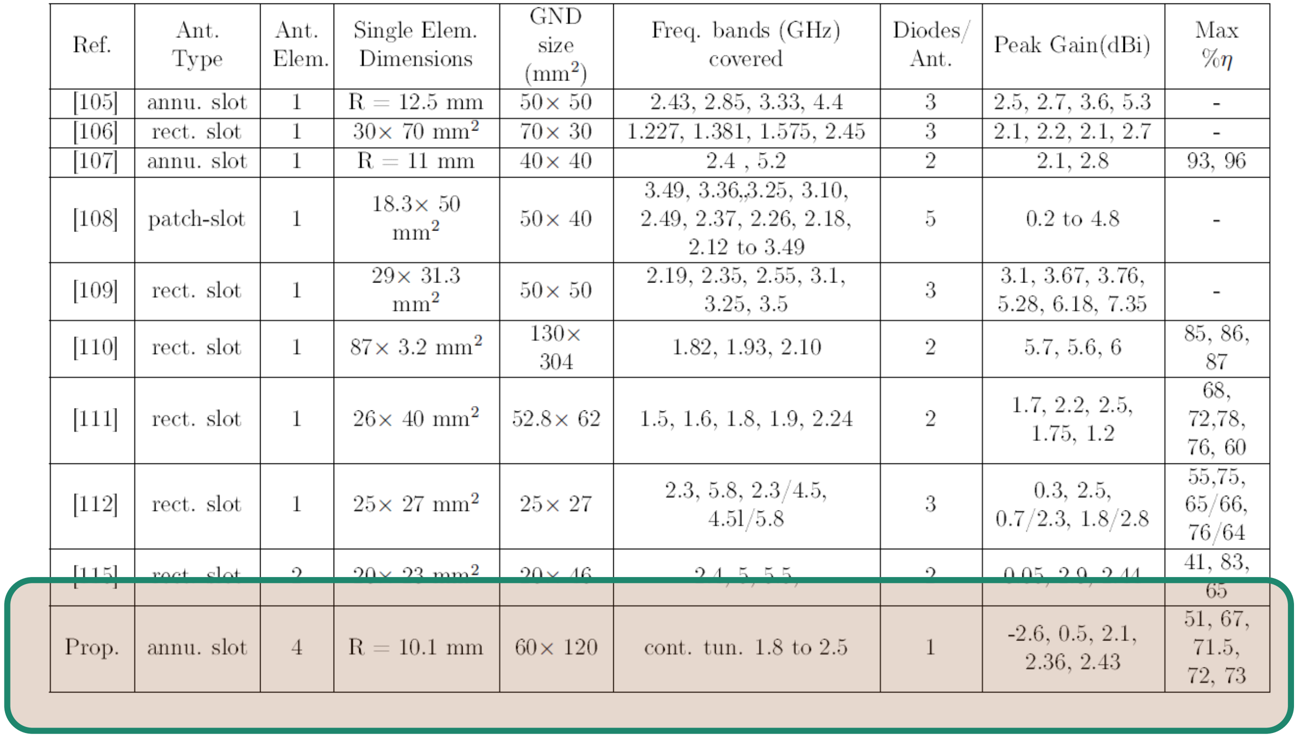
4-element MIMO Circular loop antenna

- The simulated and measured reflection coefficient and isolation curves are matching well.
- The isolation in the whole band is matching the -10 dB criteria
- Other MIMO antenna parameters were also calculated and they matched the criteria



Measured and Simulated: (a) Reflection Coefficient (S11), (b) Reflection Coefficient (S22), (c) Isolation (S12) and (d) Isolation (S13)

Proposed Design



Ref.	Ant. Type	Ant. Elem.	Single Elem. Dimensions	GND size (mm^2)	Freq. bands (GHz) covered	Diodes/ Ant.	Peak Gain(dBi)	Max $\%\eta$
[105]	annu. slot	1	R = 12.5 mm	50× 50	2.43, 2.85, 3.33, 4.4	3	2.5, 2.7, 3.6, 5.3	-
[106]	rect. slot	1	30× 70 mm^2	70× 30	1.227, 1.381, 1.575, 2.45	3	2.1, 2.2, 2.1, 2.7	-
[107]	annu. slot	1	R = 11 mm	40× 40	2.4 , 5.2	2	2.1, 2.8	93, 96
[108]	patch-slot	1	18.3× 50 mm^2	50× 40	3.49, 3.36,3.25, 3.10, 2.49, 2.37, 2.26, 2.18, 2.12 to 3.49	5	0.2 to 4.8	-
[109]	rect. slot	1	29× 31.3 mm^2	50× 50	2.19, 2.35, 2.55, 3.1, 3.25, 3.5	3	3.1, 3.67, 3.76, 5.28, 6.18, 7.35	-
[110]	rect. slot	1	87× 3.2 mm^2	130× 304	1.82, 1.93, 2.10	2	5.7, 5.6, 6	85, 86, 87
[111]	rect. slot	1	26× 40 mm^2	52.8× 62	1.5, 1.6, 1.8, 1.9, 2.24	2	1.7, 2.2, 2.5, 1.75, 1.2	68, 72,78, 76, 60
[112]	rect. slot	1	25× 27 mm^2	25× 27	2.3, 5.8, 2.3/4.5, 4.51/5.8	3	0.3, 2.5, 0.7/2.3, 1.8/2.8	55,75, 65/66, 76/64
[115]	rect. slot	2	20× 23 mm^2	20× 46	2.4, 5, 5.5,	2	0.05, 2.9, 2.44	41, 83, 65
Prop.	annu. slot	4	R = 10.1 mm	60× 120	cont. tun. 1.8 to 2.5	1	-2.6, 0.5, 2.1, 2.36, 2.43	51, 67, 71.5, 72, 73

[5] A. Ghalib, “Current Engineering methods applied to the design of MIMO antennas”, PhD Dissertation, King Fahd University of Petroleum and Minerals, Dammam, Saudi Arabia.

[14] R. Hussain, A. Ghalib and M. S. Sharawi, "Annular Slot-Based Miniaturized Frequency-Agile MIMO Antenna System," in IEEE Antennas and Wireless Propagation Letters, vol. 16, pp. 2489-2492, 2017. doi: 10.1109/LAWP.2017.2726058

Frequency Reconfigurability Analysis Using TCM

A. What about the LITERATURE?
B. WIRE ANTENNAS

Reconfigurability Analysis Using TCM

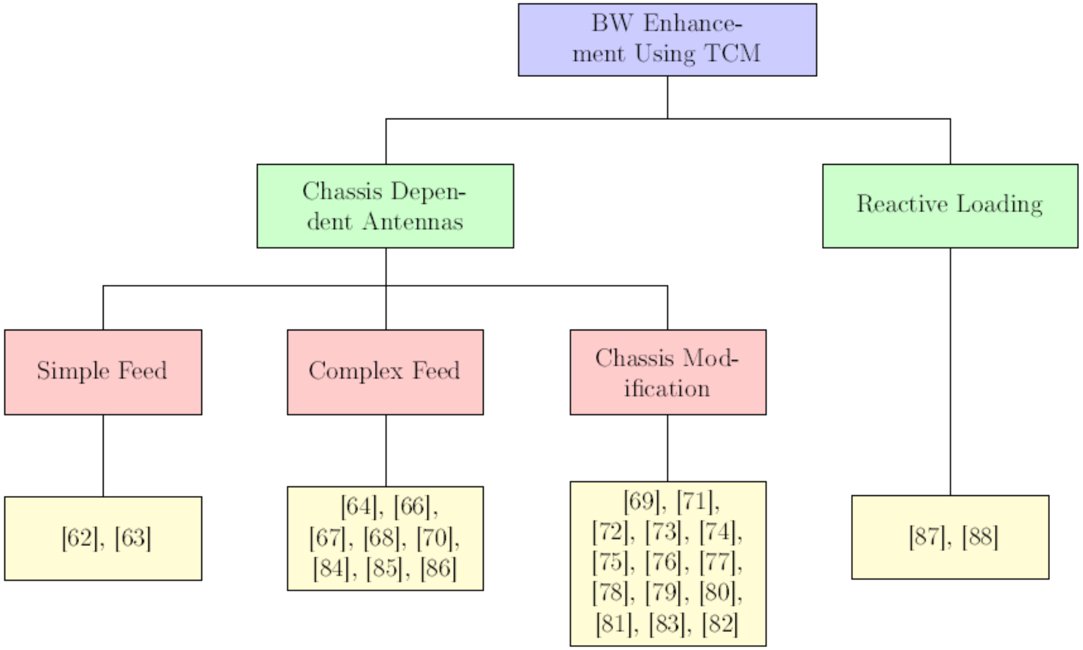
- Analyzed the Design using TCM
- For every value of capacitance we analyzed the design using TCM
- The comparison of modes were made w.r.t chassis modes
- We did the whole process for single slot case and 4-element MIMO circular slot case

- According to the LITERATURE, the modes should be affected because of the presence of the capacitance (reactance)
- In our case, the modes are **NOT AFFECTED**
- Remember the changing value of capacitance is shifting the BW of the antenna

Reconfigurability Analysis Using TCM

- Reconfigurability is just the operation of the antenna in single mode with varactors only helping in the input impedance matching
- For a well matched antenna, a frequency reconfigurable antenna will behave as a wideband antenna

Chassis Based Radiators


BW Enhancement Using TCM
Chassis Dependent Antennas
Reactive Loading
Simple Feed
Complex Feed
Chassis Modification
[62], [63]
[64], [66], [67], [68], [70], [84], [85], [86]
[69], [71], [72], [73], [74], [75], [76], [77], [78], [79], [80], [81], [83], [82]
[87], [88]

[5] A. Ghalib, “Current Engineering methods applied to the design of MIMO antennas”, PhD Dissertation, King Fahd University of Petroleum and Minerals, Dammam, Saudi Arabia

Why to use chassis Radiators?

- The use of chassis based radiators is not WRONG in all cases.
- It depends on Applications which uses low frequencies, Like Airplane, ships
- What about mobile chassis? A lot of constraints?
  - ❖ Compactness
  - ❖ Electronics
  - ❖ Frequency is high

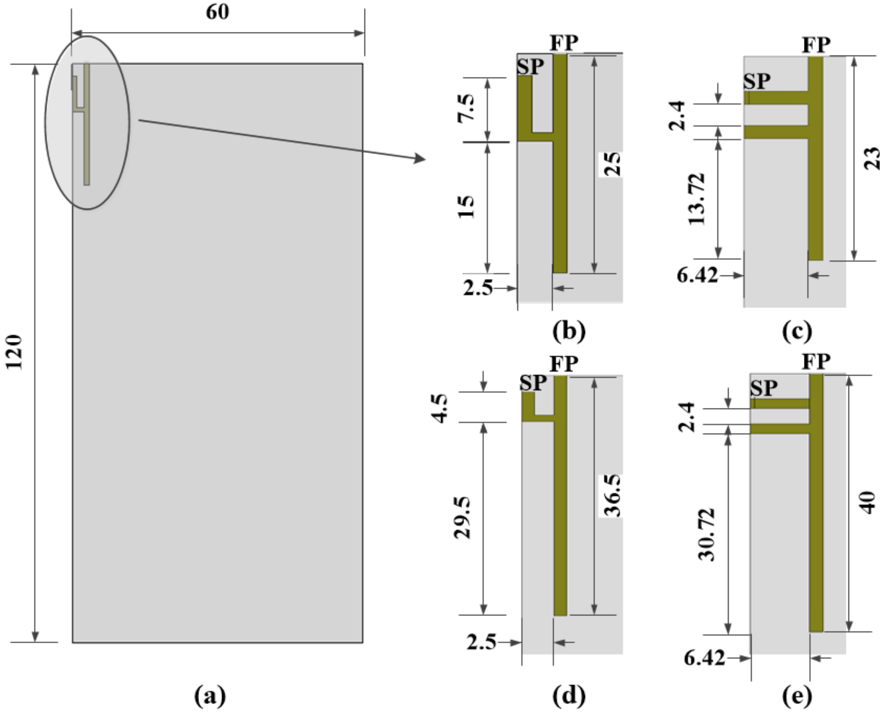
A. The current maxima's and minima's are distinct unlike antenna based radiators
B. The chassis modes are easy to excite
C. Does it Justify the use of chassis based radiators

Chassis Based Radiators

For frequencies greater than 1 GHz, we showed for the first time that the antenna is the element responsible for the radiation and not the mobile chassis. So, the use of the chassis for frequencies greater than 1 GHz is unrealistic approach.

Chassis Based Radiators

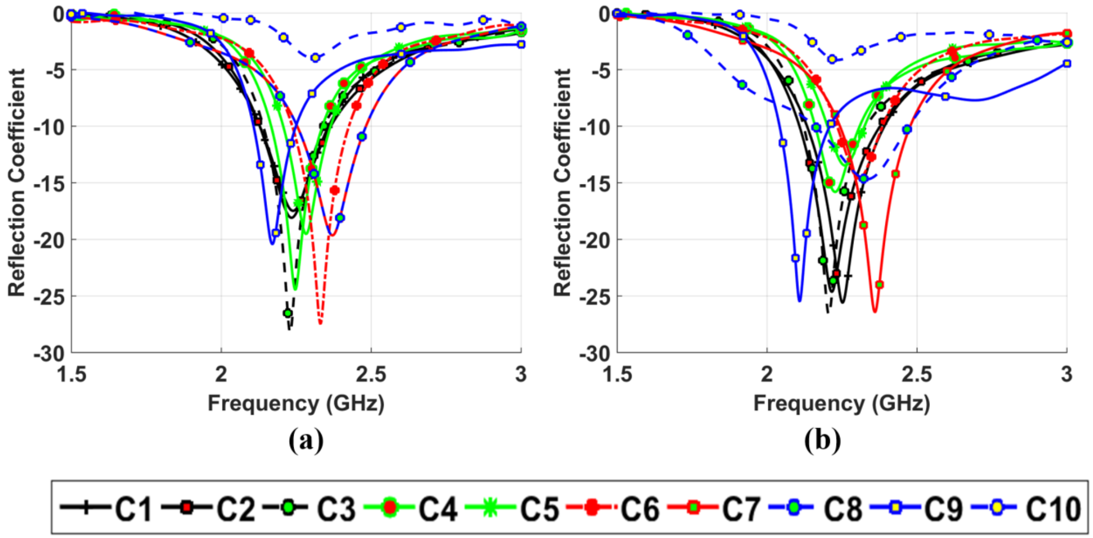
Design geometries



All designs are made on RO4350 substrate having a dielectric constant of 3.48. The thickness of the substrate is 0.8 mm.

Design geometries, where (a) Antenna element on mobile chassis (b) Design 1, PIFA antenna resonating at 2.2 GHz, (c) Design 2, Monopole antenna resonating at 2.2 GHz, (d) Design 3, PIFA antenna resonating at 0.93 GHz and (e) Design 4, Monopole antenna resonating at 0.95 GHz. SP and FP represents the shorting point and the feeding point respectively. All dimensions are in mm.

Chassis Based Radiators



(a)

(b)

Reflection Coefficient Curves for (a) Design 1, (b) Design 2

C1 to C10 refers to the reduction in size by 0% (no reduction),16%, 30%, 44%, 56%, 66%, 75%, 83%, 90% and 94% of the original chassis size.

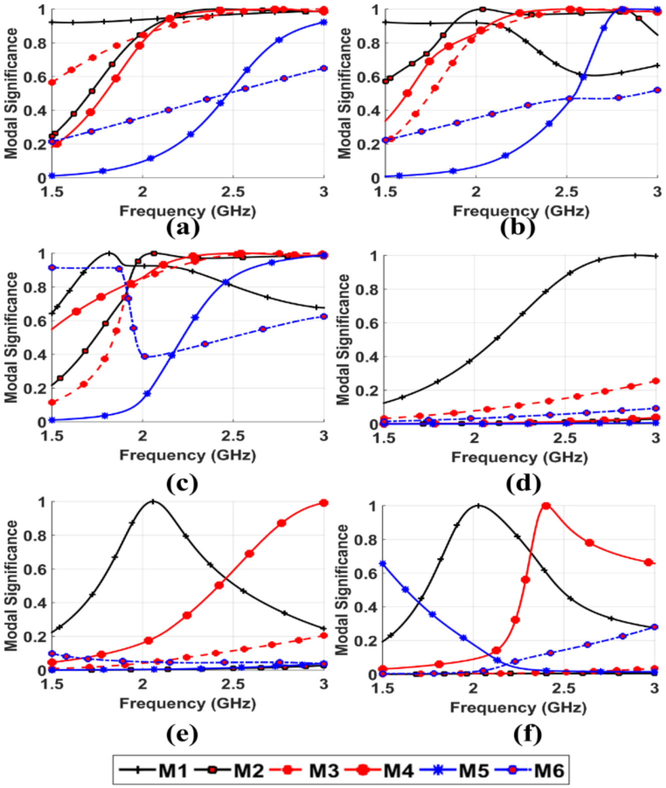
A. The impedance BW for both the design is not affected even when the size of the chassis was reduced up to 90%
B. This means that the use of such large chassis as a main radiating element for frequencies greater than 2 GHz is UNREALISTIC

Chassis Based Radiators

TCM Analysis

- As expected, The presence of the antenna affects the chassis modes
- For a 90% reduced chassis, **NO mode** is present in the radiating BW region i.e. at 2.2 GHz
- How can chassis radiate then?
- **The presence of the antenna has shifted the mode to desired frequency band.**

It's the antenna that is the main radiator and not the chassis



Modal Significance curves (a) Chassis 120×60 mm^2, (b) Design 1, (c) Design 2, (d) 90% reduced chassis (40×20 mm^2), (e) Design 1 on 90% reduced chassis, (f) Design 2 on 90% reduced chassis.

Conclusions

- Slots do not produce any new mode
- Chassis modes are modified based on the location, shape and size of the slot
- A 4-element circular slot MIMO antenna design is presented, operating between 1.8 GHz to 2.45 GHz
- Slots introduced on the chassis in symmetrical fashion affects the chassis modes less as compared to the slots introduced in asymmetrical fashion (Single/ MIMO)
- The Physical mechanism of frequency reconfigurability was explained

Conclusions

- The physical operation of DGS was explained
- A systematic procedure for the placement of the DGS was presented
- On an average 11 dB of isolation enhancement was achieved

- The use of the chassis as a main radiating element for frequencies greater than 1 GHz is unrealistic

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Thank You

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